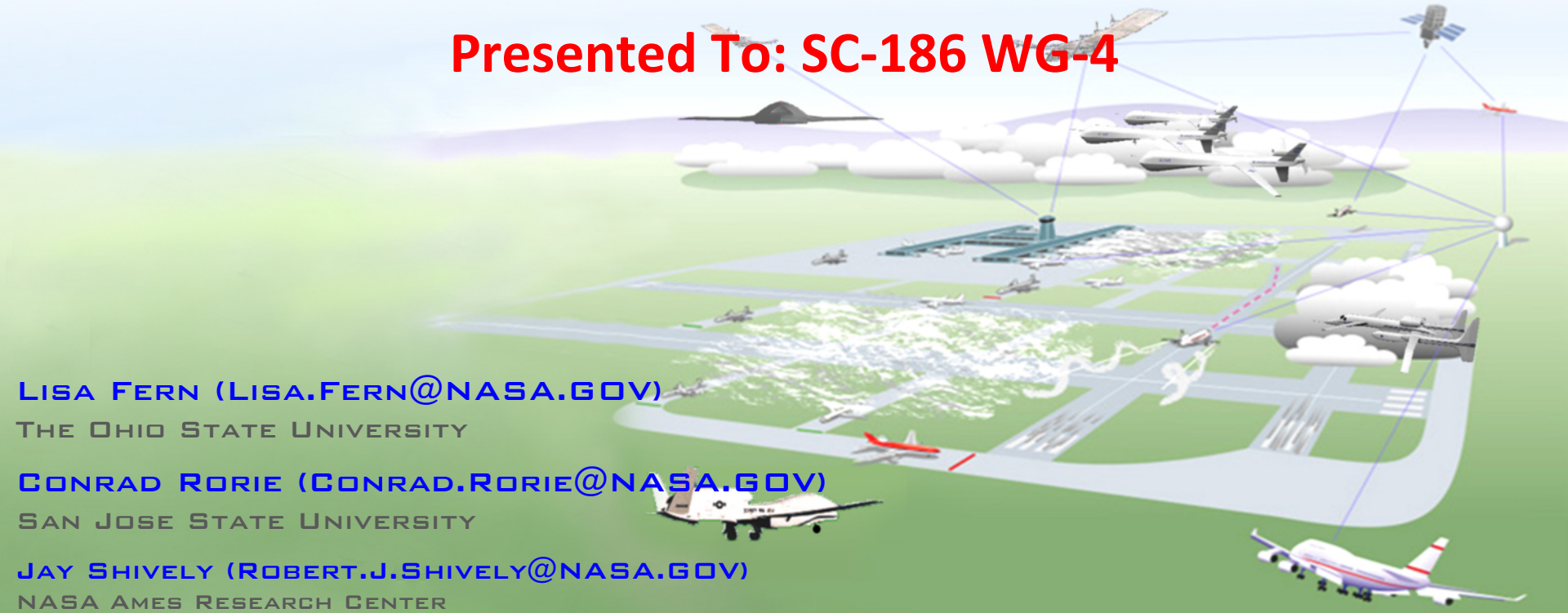
National Aeronautics and Space Administration

UAS Integration into the NAS: Detect and Avoid Display Evaluations in Support of SC-228 MOPS Development

Presented To: SC-186 WG-4



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Background

- Goal: Provide data on the effect of various Detect and Avoid (DAA) display features with respect to pilot performance of the self-separation function in order to determine the minimum information requirements for DAA displays
  1. What is the pilot contribution to the self-separation timeline in terms of expected response time to detect, determine and execute a maneuver in response to a potential loss of well clear?
  2. What configuration of display elements meets a minimum acceptable level of performance? What, if any, level of pilot maneuver guidance is required to support this performance?

Background

- Display Types:
  - Informative: Provides essential information of a hazard that the remote pilot may use to develop and execute an avoidance maneuver. ***No maneuver guidance or decision aiding is provided to the pilot***.
  - Suggestive: ***Provides a range of potential resolution maneuvers to avoid a hazard with manual execution***. An algorithm provides the pilot with maneuver decision aiding regarding advantageous or disadvantageous maneuvers.
  - Directive: ***Provides specific recommended resolution guidance to avoid a hazard with manual or automated execution***. An algorithm provides the pilot with specific maneuver guidance on when and how to perform the maneuver.

Background

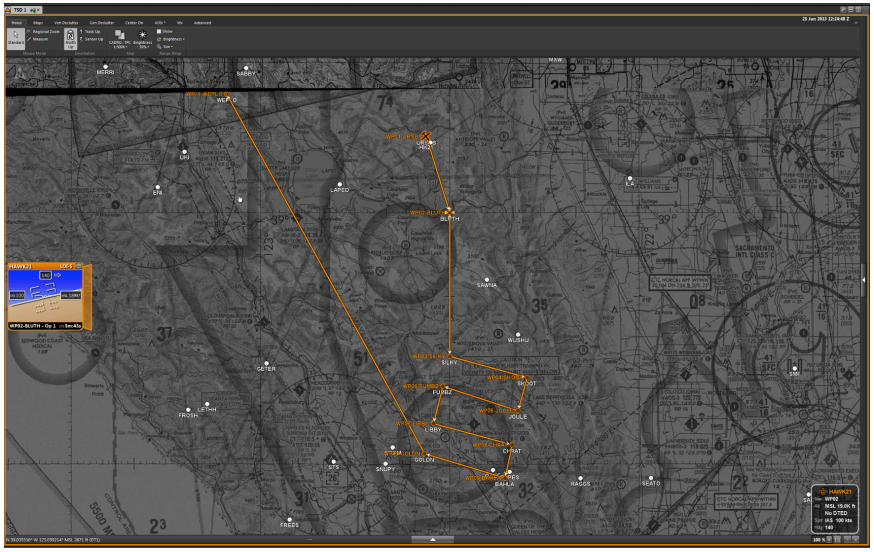
- Approach: Conduct a series of iterative human in the loop experiments, in a representative simulation environment, with different display configuration to objectively measure pilot performance on maintaining well clear
  - Key metrics: pilot response time, losses of well clear, severity of losses of well clear
  - Three simulations have been conducted: PT4, iHITL, PT5
    - Displays are modified/improved/changed based on data/observations
    - Displays are carried through to new HITLs to create anchors or linkages to previous data for comparison
    - New displays are developed for test
    - Test/simulation environment/protocols also updated and improved between HITLs

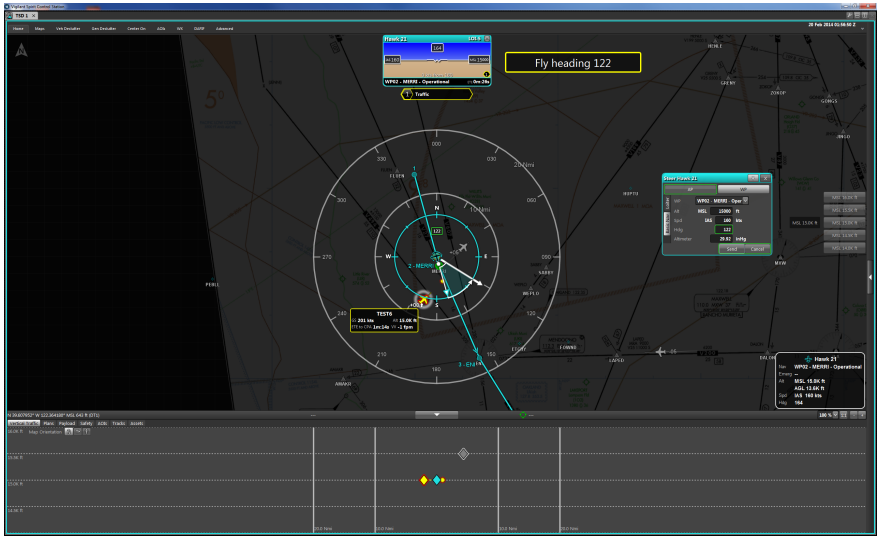
Simulation Environment

- Emulation of representative environment:
  - UAS Ground Control Station (GCS) with DAA Display
  - DAA system components:
    - Surveillance
    - Threat detection and alerting
    - Suggestive and directive guidance
  - Air Traffic Control
  - Simulated Manned Traffic
- Integrated via NASA's Live, Virtual, Constructive (LVC) architecture

Simulation Environment: Ground Control Station (GCS)

- The Vigilant Spirit Control Station (VSCS) developed by the Air Force Research Laboratory (AFRL)
- Main Features:
  - Robust, flexible interface
  - Realistic control and navigation displays
  - System status and health monitoring
  - STANAG 4586 Compliant
  - Multi-UAS control with VSCS has been tested in simulation and flight by AFRL
- Current UAS in the NAS version modifications/additions:
  - Single pilot – single UAS control
  - NAS-compatible database (low- and high- altitude charts with navigational aids/"fixes")
  - Integrated traffic display





Simulation Environment: DAA System

- The Java Architecture for DAA Modeling and Extensibility (JADEM) was developed by the UAS in the NAS project at NASA Ames Research Center
- Main Functions:
  - Emulate surveillance parameters for various sensor types
    - e.g., ADS-B, active radar, TCAS, etc.
  - Receive state information from simulated traffic (MACS)
    - Determine which aircraft to show on traffic display(s) based on surveillance parameters
  - Receive trajectory information from UAS ownship (VSCS)
  - Queries all intruders for potential conflicts with ownship
  - Assigns intruders alert levels based on given thresholds
  - Host self-separation and collision avoidance algorithms which can provide conflict resolution guidance

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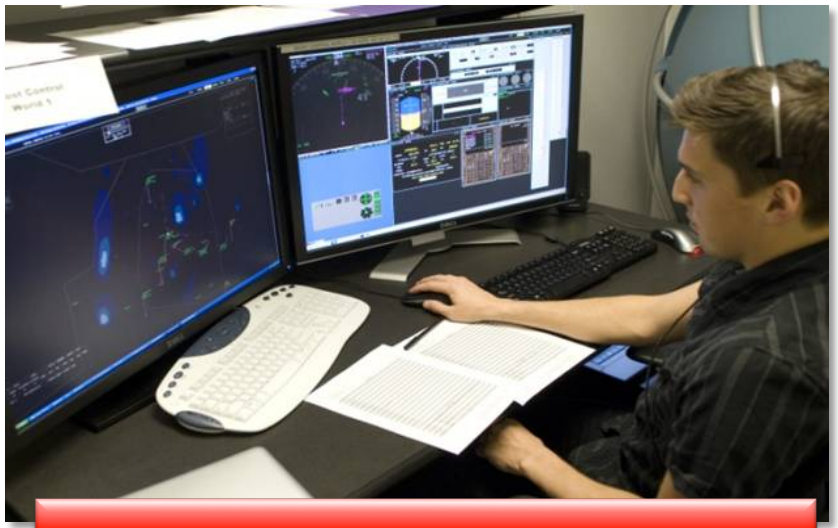
Simulation Environment: Draft MOPS Alerting Structure

Symbol	Name	Pilot Action	Buffered Well Clear Criteria	Alerting Time Threshold	Aural Alert Verbiage
	DAA Warning Alert	• ***Immediate action required*** • Notify ATC as soon as practicable after taking action	DMOD = 0.75 nmi HMD = 0.75 nmi ZTHR = 450 ft modTau = 35 sec	25 sec (TCPA approximate: 60 sec)	"Traffic, Maneuver Now"
	DAA Corrective Alert	• On current course, ***corrective action required*** • Coordinate with ATC to determine an appropriate maneuver	DMOD = 0.75 nmi HMD = 0.75 nmi ZTHR = 450 ft modTau = 35 sec	55 sec (TCPA approximate: 90 sec)	"Traffic, Avoid"
	DAA Preventive Alert	• On current course, corrective action ***should not be required*** • Monitor for intruder course changes • Talk with ATC if desired	DMOD = 1.0 nmi HMD = 1.0 nmi ZTHR = 700 ft modTau = 35 sec	55 sec (TCPA approximate: 90 sec)	"Traffic, Monitor"
	Remaining Traffic	• No action expected	Within surveillance field of regard	X	N/A

Simulation Environment: Multi Aircraft Control Station (MACS)

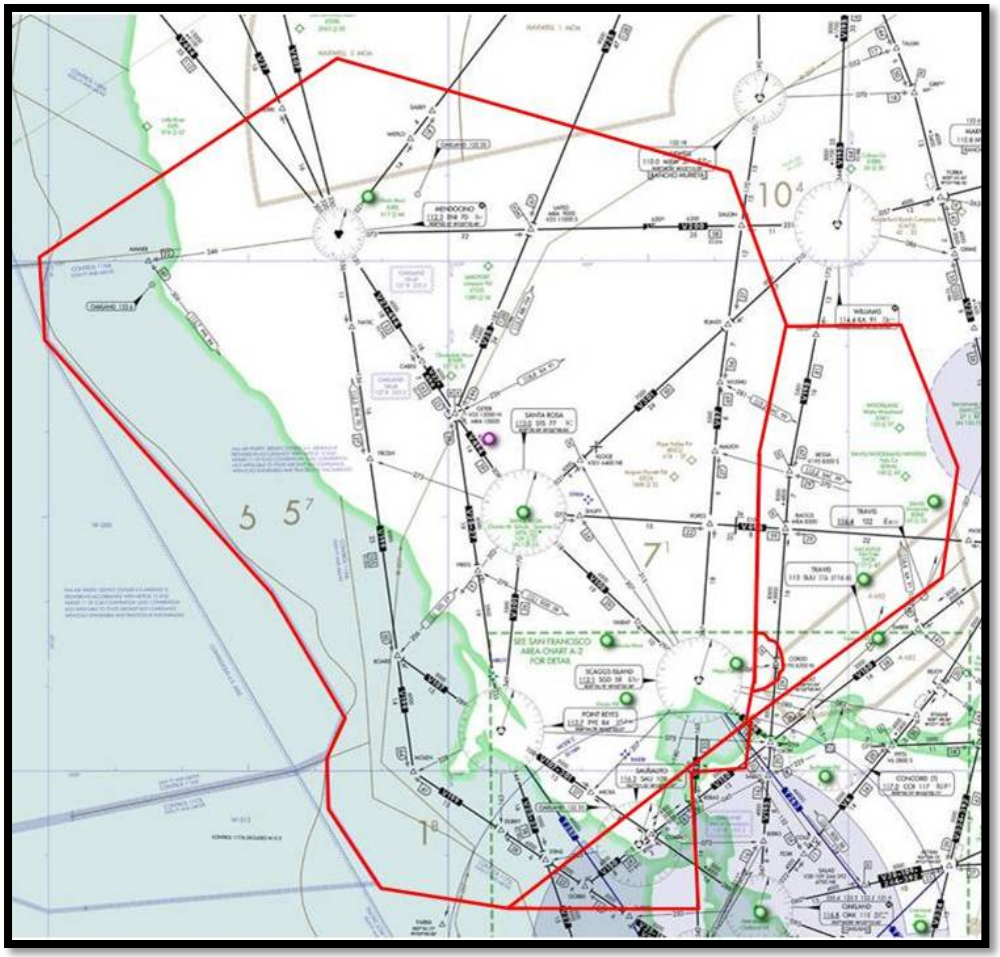
- The Multi Aircraft Control Station (MACS) developed by the Airspace Operations Laboratory (AOL) at NASA Ames Research Center
- Provides emulation of ground- and air- side Air Traffic Control (ATC) operations
  - Air Traffic Controller work stations
  - Simulated traffic generator
  - Psuedo pilot work stations
  - IFR and VFR simulated traffic
  - Traffic scenarios in Oakland Center (ZOA 40/41) airspace based on current day traffic patterns

Air Traffic Control Station



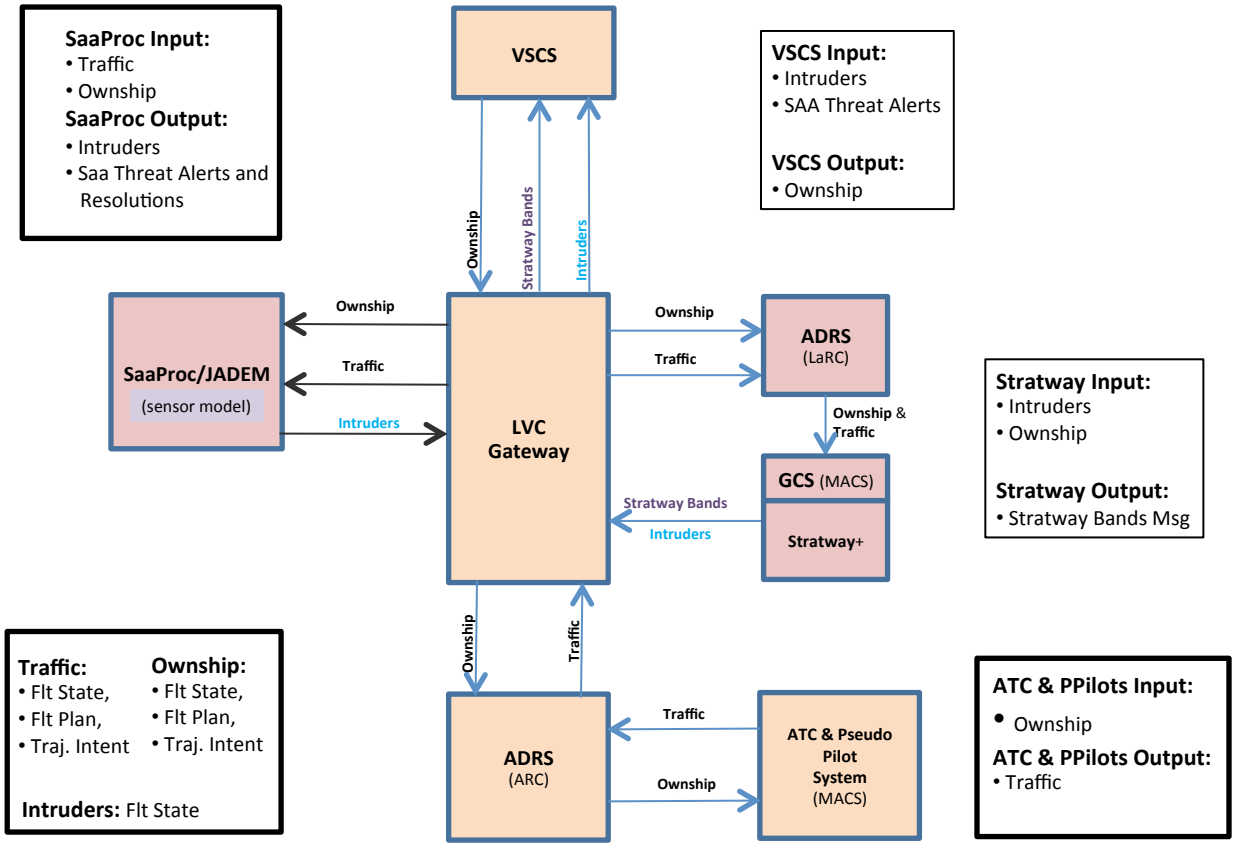
Pseudo Pilot Station

Simulation Environment: Multi Aircraft Control Station (MACS)



- Oakland Center ZOA 40/41
  - Class A & E
  - Current day IFR and VFR traffic flows
- UAS mission scenario derived from FAA CONOPS scenarios (combination of “Loiter for Surveillance” and “Grid Pattern”)

Simulation Environment: LVC Architecture



Background

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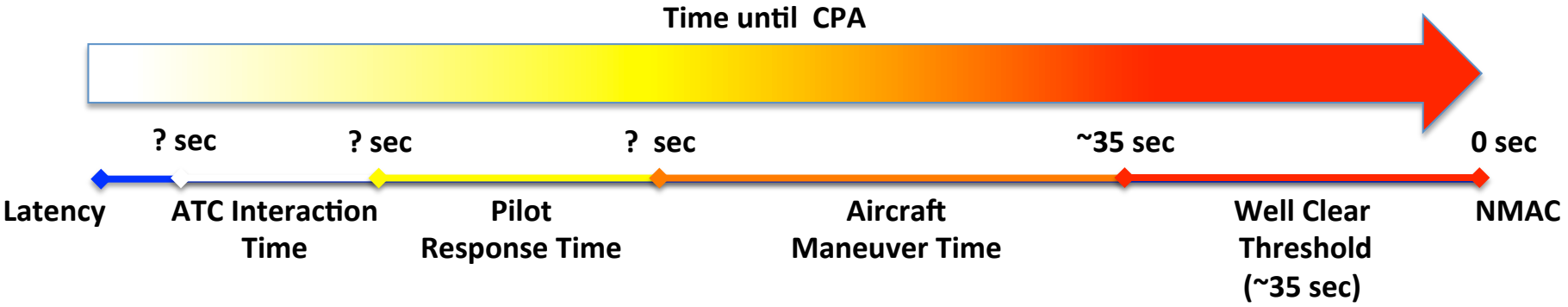
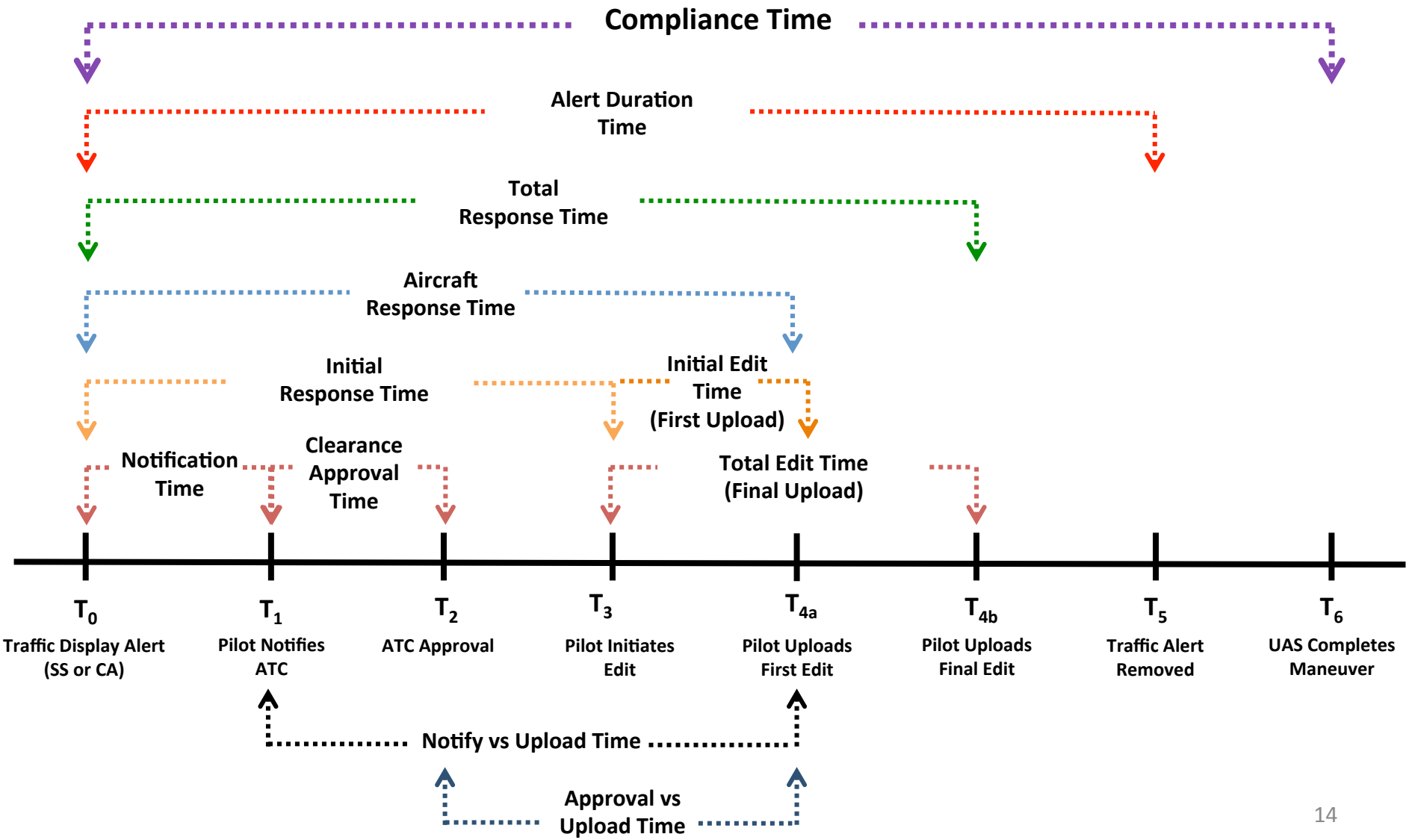
DAA/Traffic Avoidance Timeline

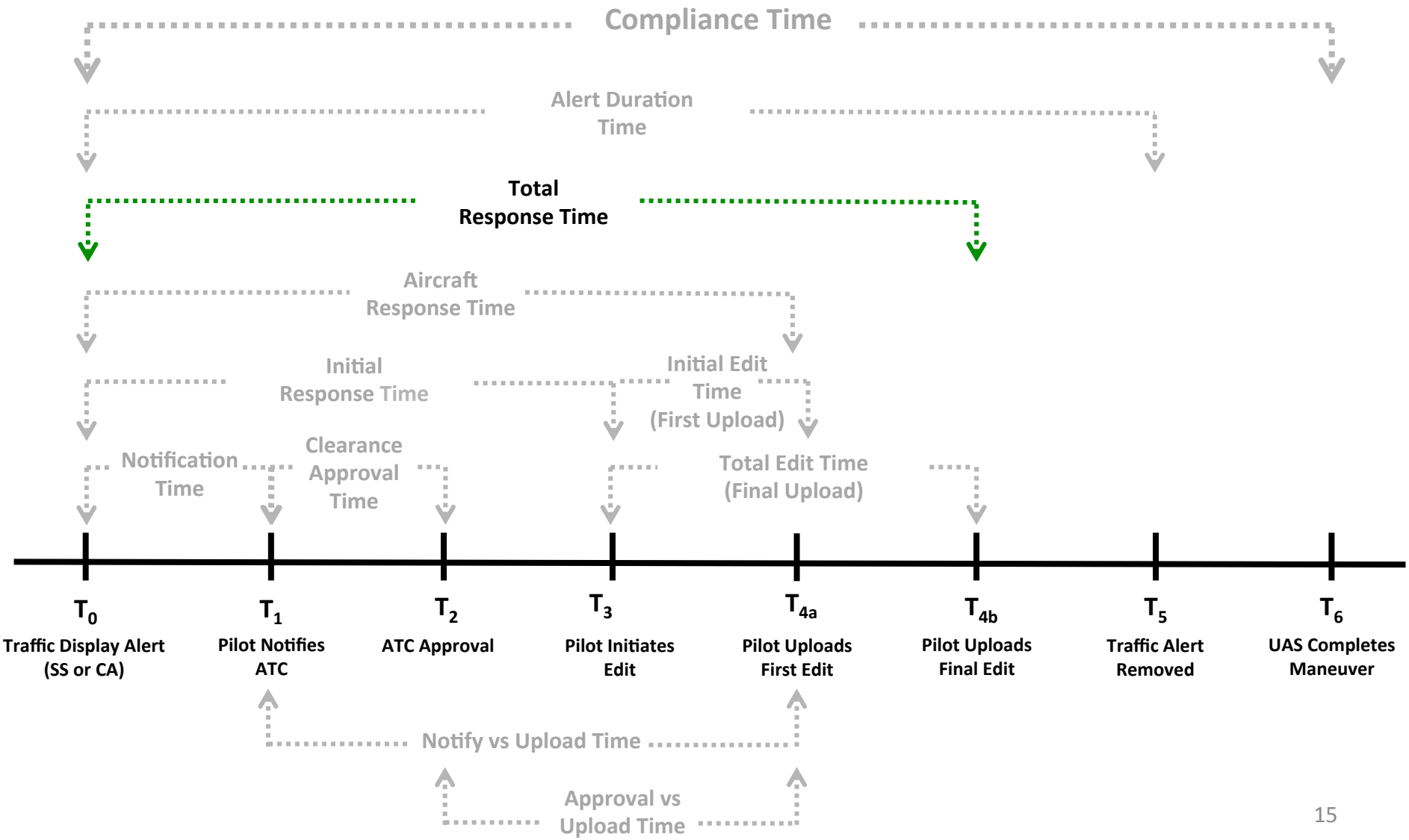


TOTAL RESPONSE TIME:
Detect Intruders
Pilots Determine Resolution
Negotiate Clearance with ATC and uplink maneuver to aircraft

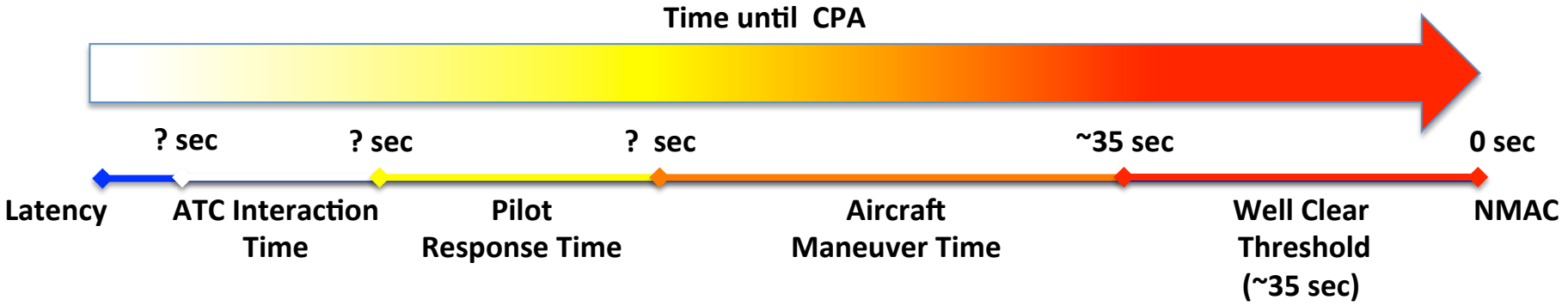
Pilot-DAA Timeline



Pilot-DAA Timeline



DAA/Traffic Avoidance Timeline



TOTAL RESPONSE TIME:
Detect Intruders
Pilots Determine Resolution
Negotiate Clearance with ATC and uplink maneuver to aircraft

PT4 – Experimental Design

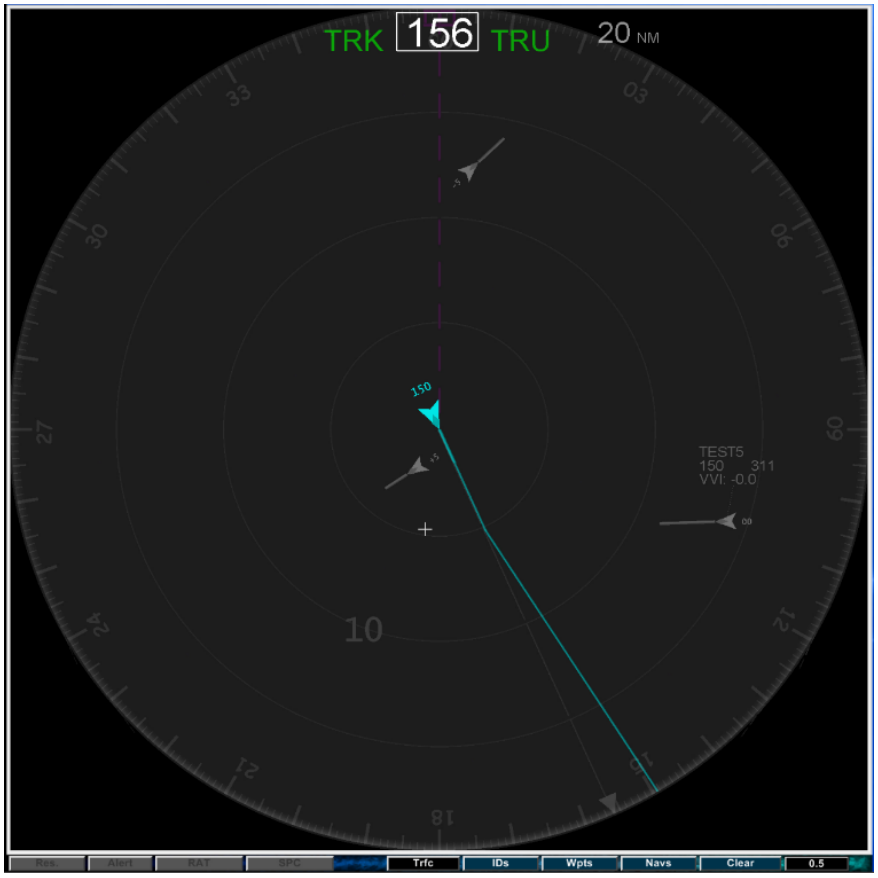
- Goal: Evaluate candidate Detect and Avoid (DAA) displays and algorithms with respect to self-separation and collision avoidance.
  - What are the appropriate alerting thresholds for self separation?
  - What are the minimum information requirements for DAA displays?
  - Is there a performance difference between integrated and standalone displays?
  - What advanced display features improve pilot performance on maintaining well clear from other traffic?
- What advanced display features improve pilot performance on maintaining well clear from other traffic?
  - Experimental Design: Mixed Factorial Design
  - 2 (Display: Standalone, Integrated)
  - X 2 (Information: Basic, Advanced)
  - X 2 (Self-Separation Alerting Threshold)

PT4 – Information Level

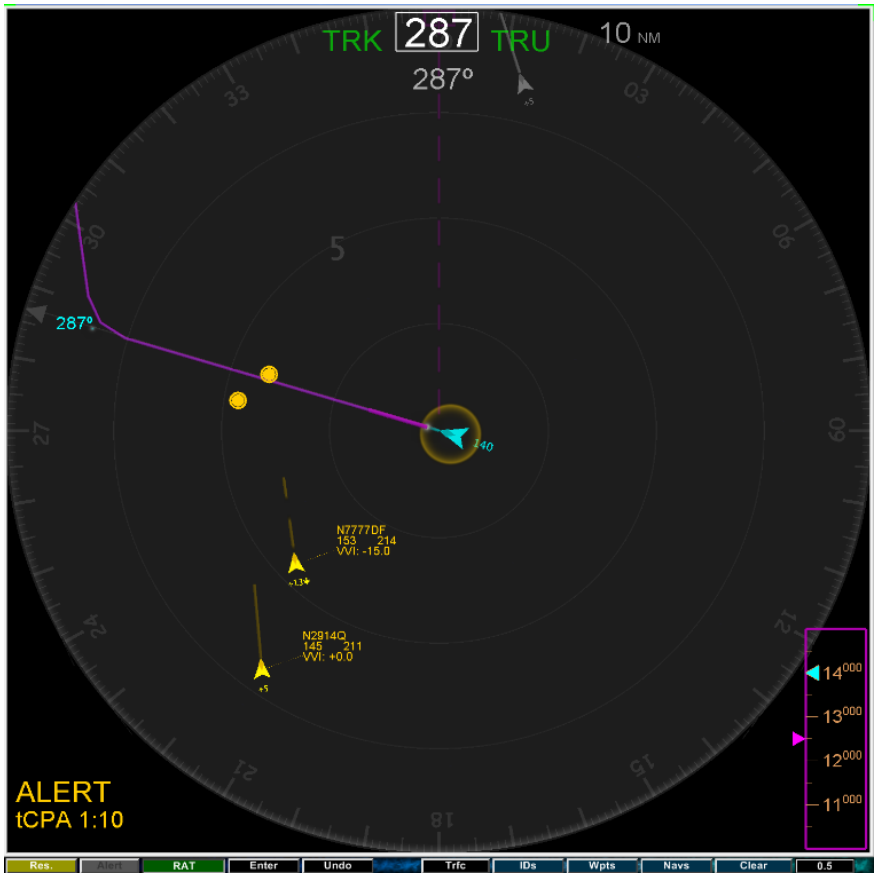
- Display Information Level: Basic versus Advanced
  1. Basic presents minimum information requirements only
     - Implementation identical as possible between Standalone and Integrated displays
     - Based on separate literature/requirements reviews by NASA and AFRL HMI teams
     - Vetted with FAA tech center (based on study they were running)
     - Similar to DO-317B (was a source document)
     - Alerting considered part of the min set
  2. Advanced information elements:
     - Implementation different between Standalone and Integrated displays
     - Additional alerting information (predictive CA)
     - Time to and location of predicted CPA (intruder and ownship)
     - Pilot guidance
       - Trial/vector planner (suggestive)
       - Maneuver recommendations (directive)
     - Vertical situation display (Integrated only)

PT4 – Standalone Displays

Basic



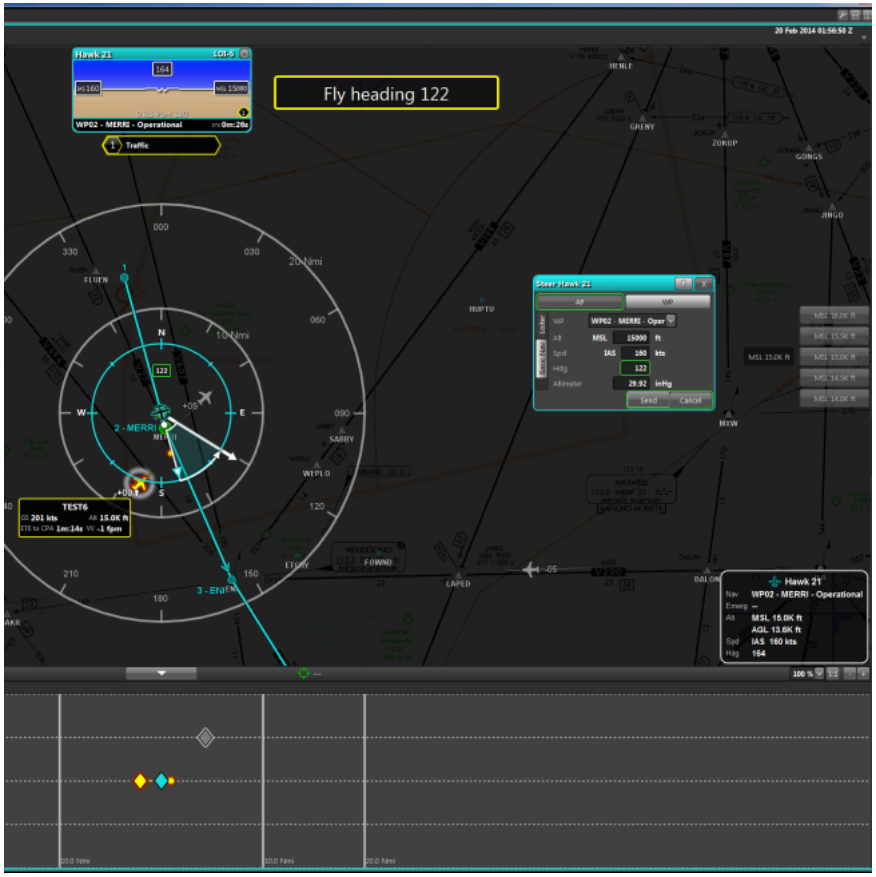
Advanced



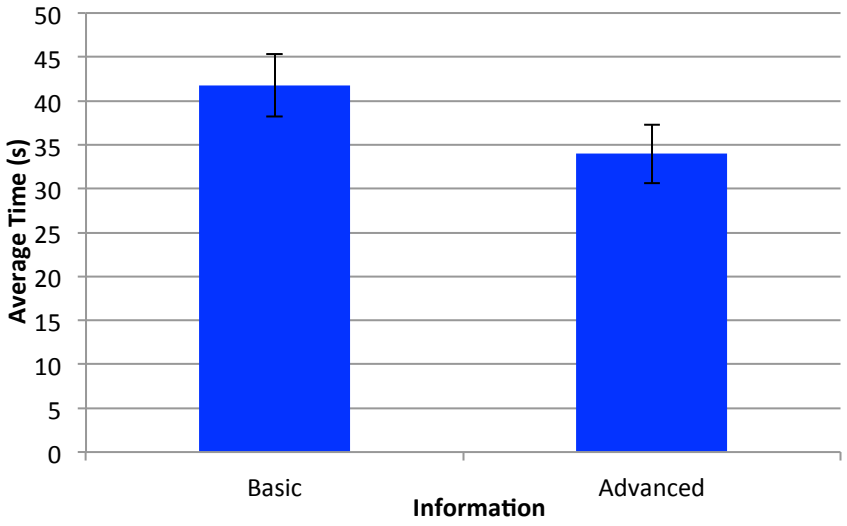
PT4 – Integrated Displays

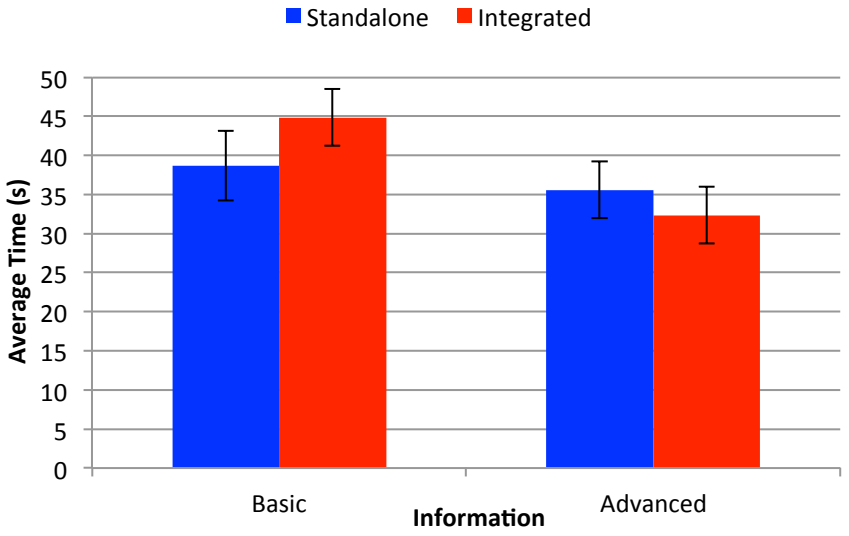
Basic

Advanced



PT4 – Total Response Time Results

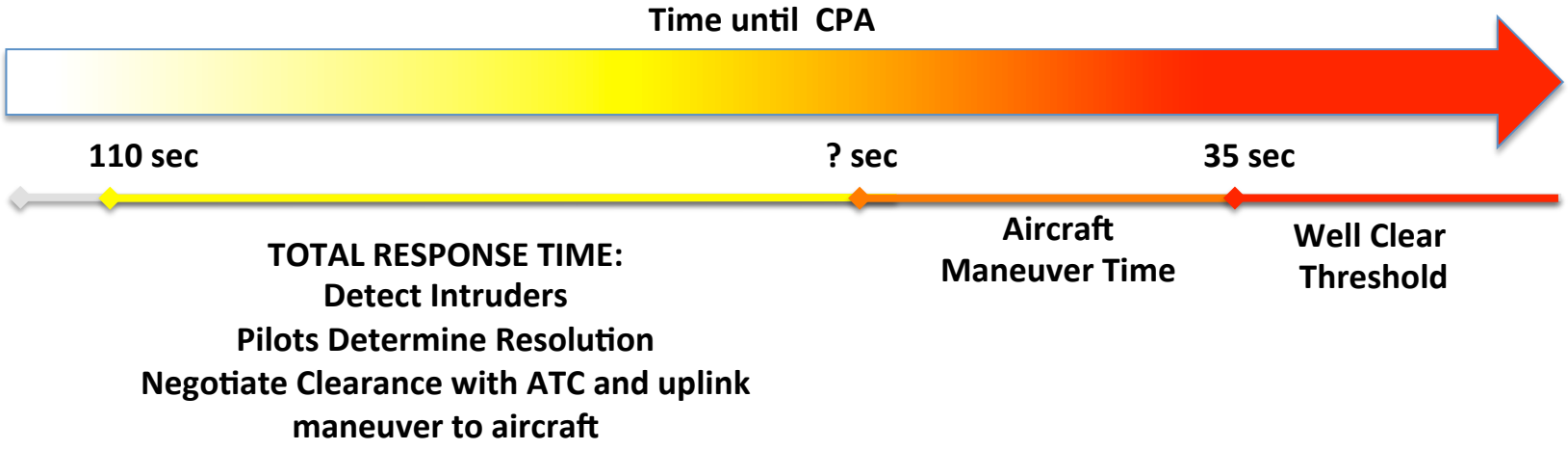




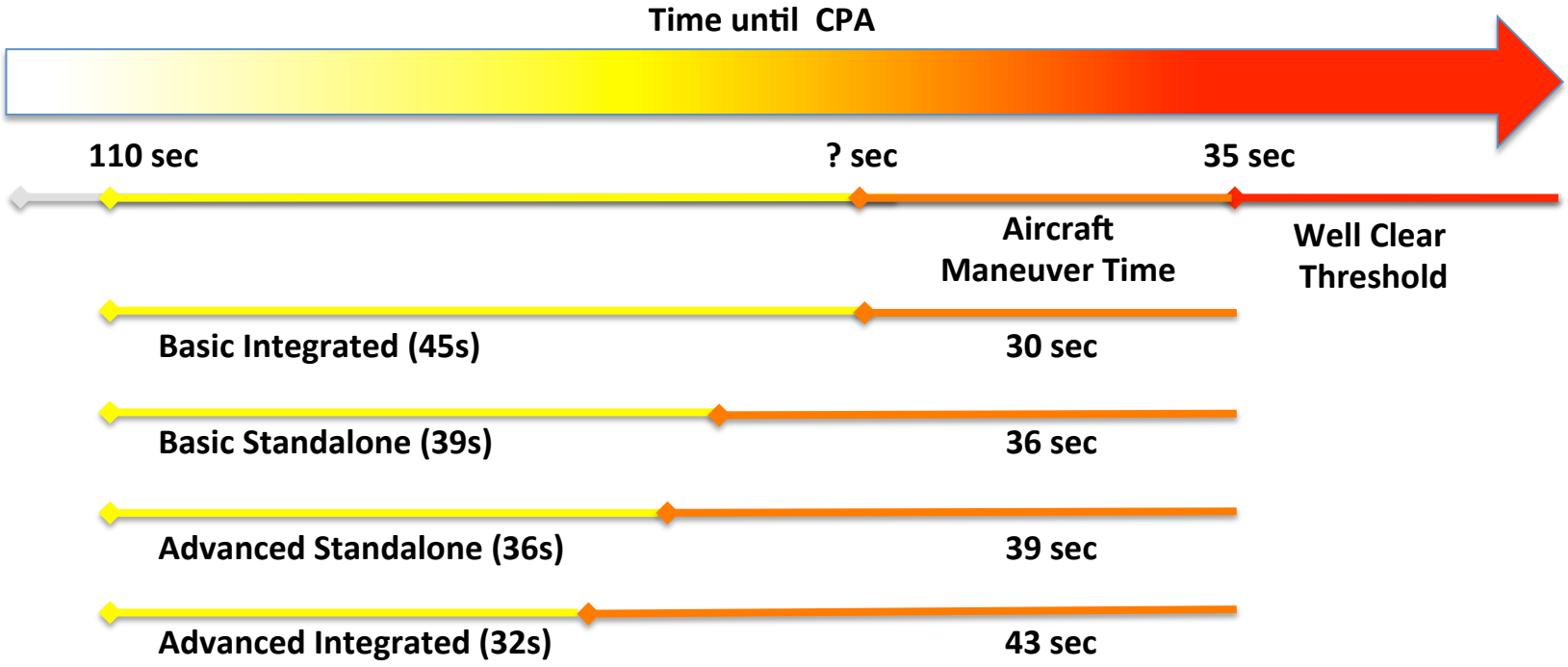
- There was a significant main effect of Information on Total Response Time, $p < .05$
  - Advanced was significantly faster (by 13.79 seconds on average) compared to Basic
- Pilots took an average of **37.87 seconds** to complete their final edit in response to SS/CA alerts (from first alert appearance)
  - Basic = 47.77 sec
  - Advanced = 33.98 sec

- There was not a significant interaction of Information by Display for Total Response Time, $p > .05$
- Pilots took an average of **37.87 seconds** to complete their final edit in response to SS/CA alerts (from first alert appearance)
  - Basic Standalone = 38.68 sec
  - Basic Integrated = 44.86 sec
  - Advanced Standalone = 35.60 sec
  - Advanced Integrated = 32.35 sec

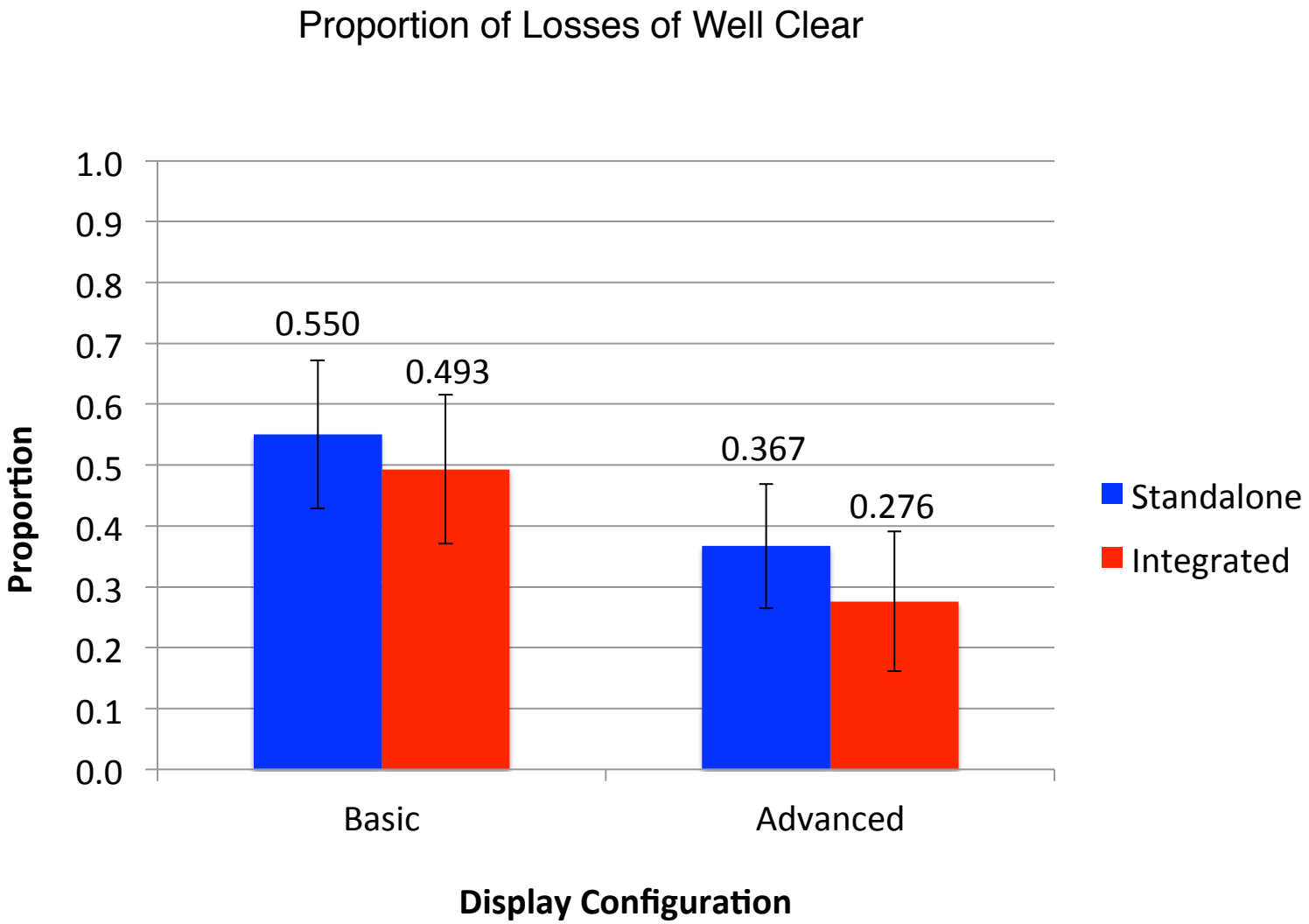
DAA/Traffic Avoidance Timeline



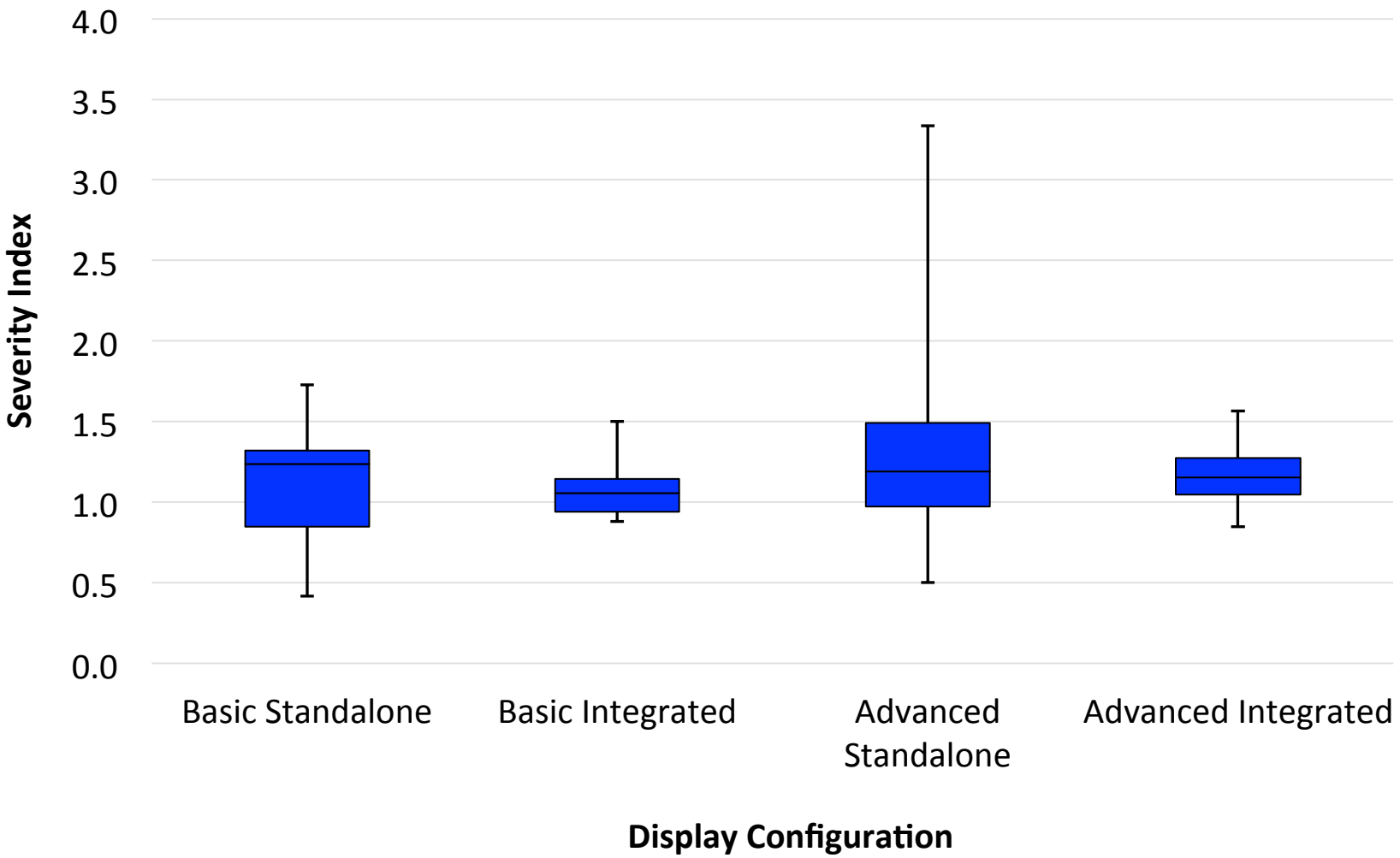
PT4 – Response Time Results



PT4 – Losses of Well Clear



PT4 – WCV Severity



PT4 – Results Summary

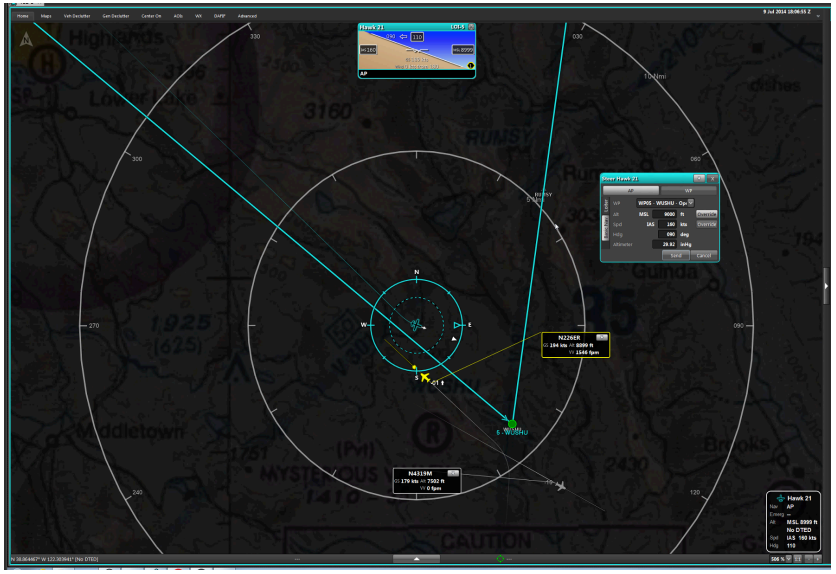
- Consistent advantage seen for Advanced over Basic displays in pilot response times
  - Overall, the Advanced displays had a faster Total Response Time (from initial alert appearance to the final maneuver upload) compared to Basic (14s faster, on average)
- There were no significant differences between the Standalone and Integrated condition
- No significant differences in proportion or severity of losses of well clear, however:
  - Advanced trended toward lower rates of LoWC than basic
  - No difference between Standalone and Integrated in rates of LoWC
  - Severity of well clear about the same across all displays

iHITL – Experimental Design

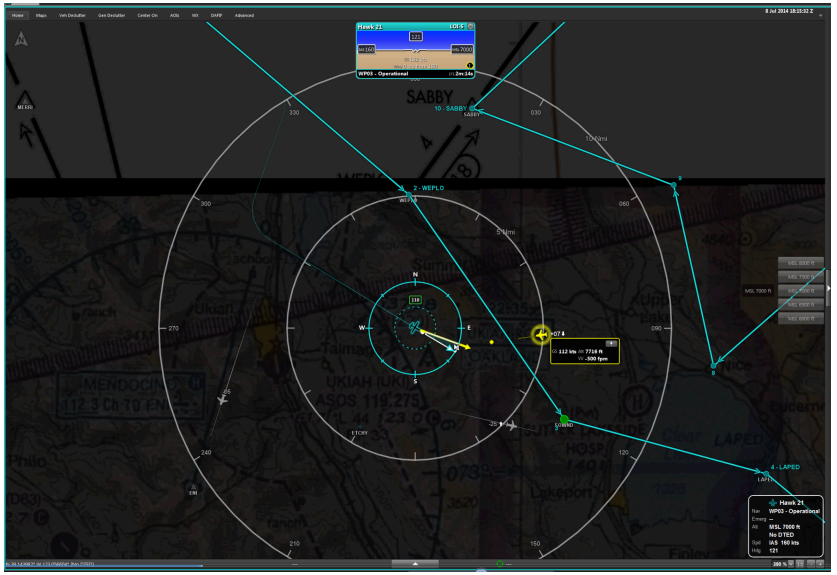
- Goals:
  1) Determine the individual contributions of the various PT4 advanced display features to pilots' response times and ability to maintain well clear
  2) Introduce non-cooperative intruders to examine effect of different sensor ranges on pilots ability to maintain well clear
- One-Way Repeated Measures Factorial: Display Information Level (4 Level; Within Subjects)
  - D1: Advanced Display with Information Only **(Informative)**
  - D2: Advanced Display with Information + Vector Planner **(Suggestive)**
  - D3: Advanced Display with Information + Auto Resolutions **(Directive)**
  - D4: Advanced Display with Information + Vector Planner + Auto Resolutions **(Suggestive + Directive)**
    - Roughly same as 'Advanced' suite in PT4
- Embedded Variable
  - *Intruder Equipage* (manipulated within each scenario)
    - Transponder-equipped (detected via UAS's ADS-B)
    - No Transponder (detected via UAS's on-board RADAR)

iHITL – Display Conditions

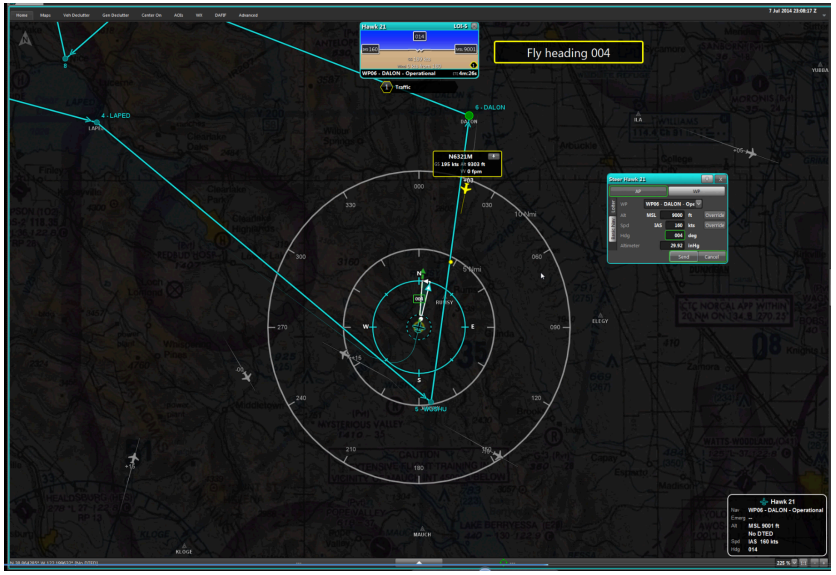
D1



D2

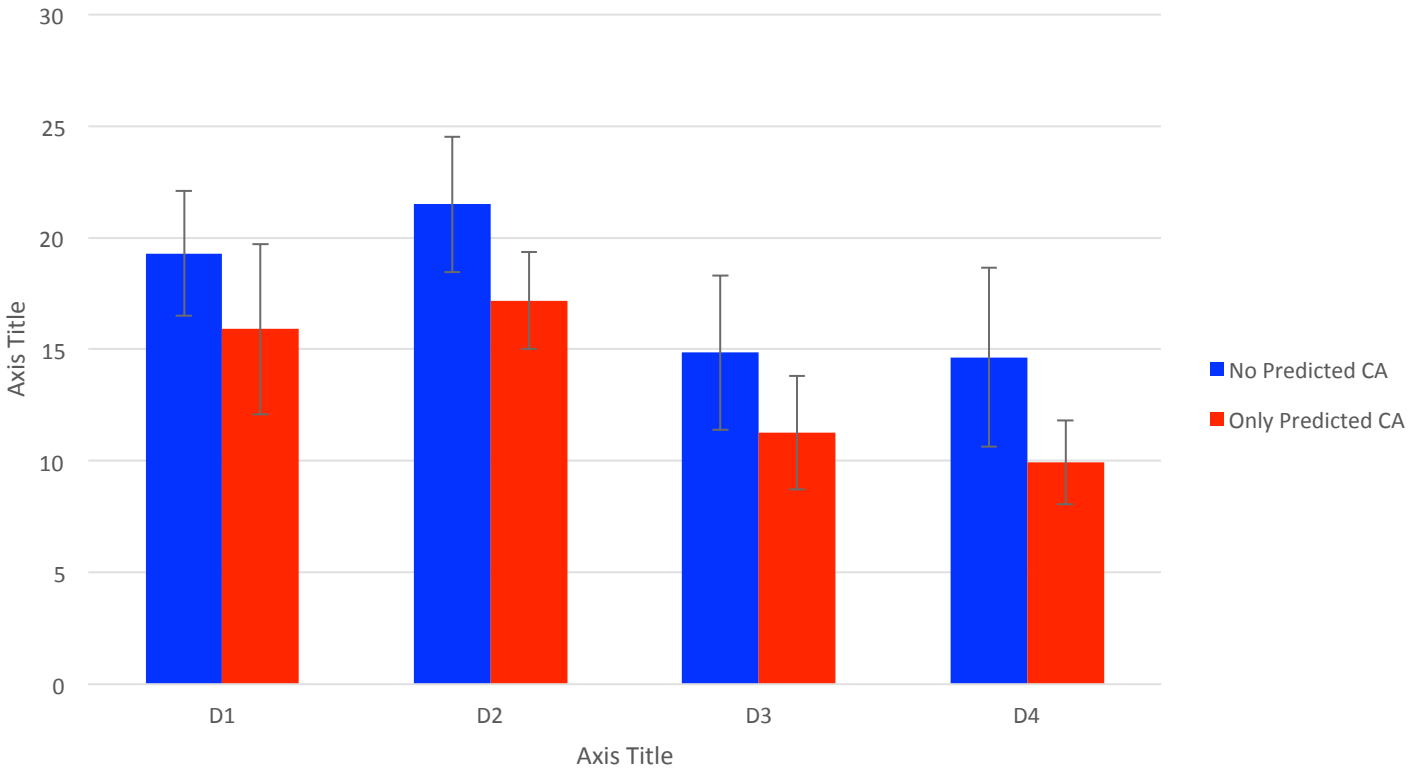


D3



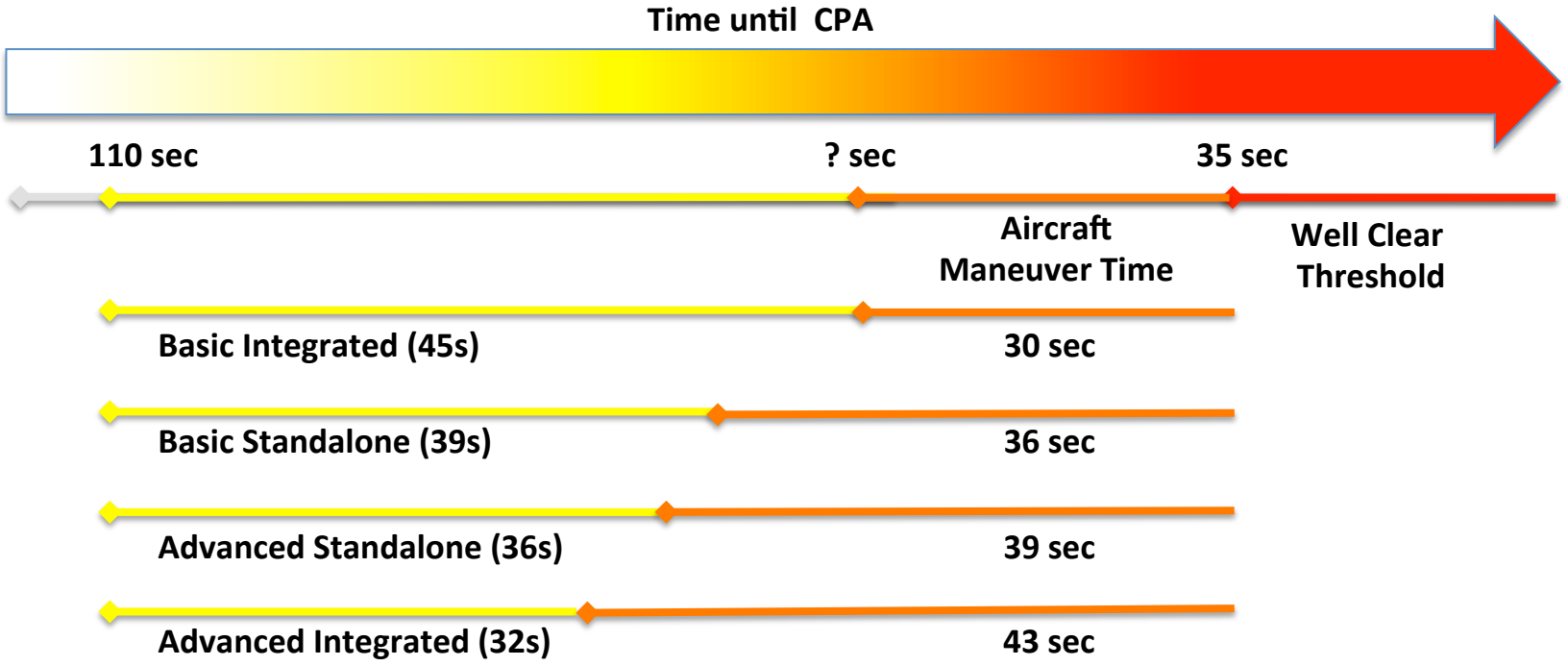
D4

iHITL – Total Response Time Results

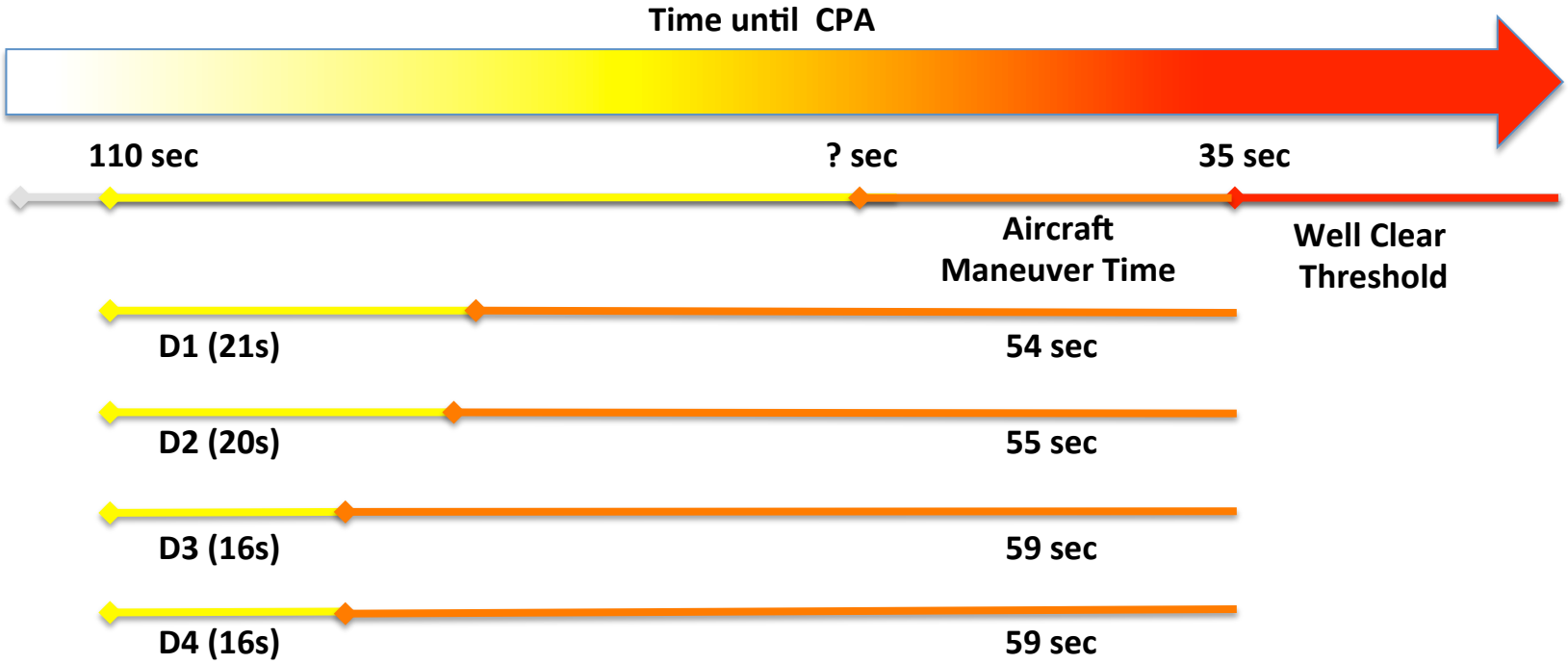


- Predictive SS = encounters that are predicted to lose well clear at any point during the encounter
- There was a near significant effect of Display on Total Response Time for Predictive SS alerts, p = .056
- Pilots took an average of **16.22 seconds** to complete their final edit in response to Predictive SS alerts (from first alert appearance)

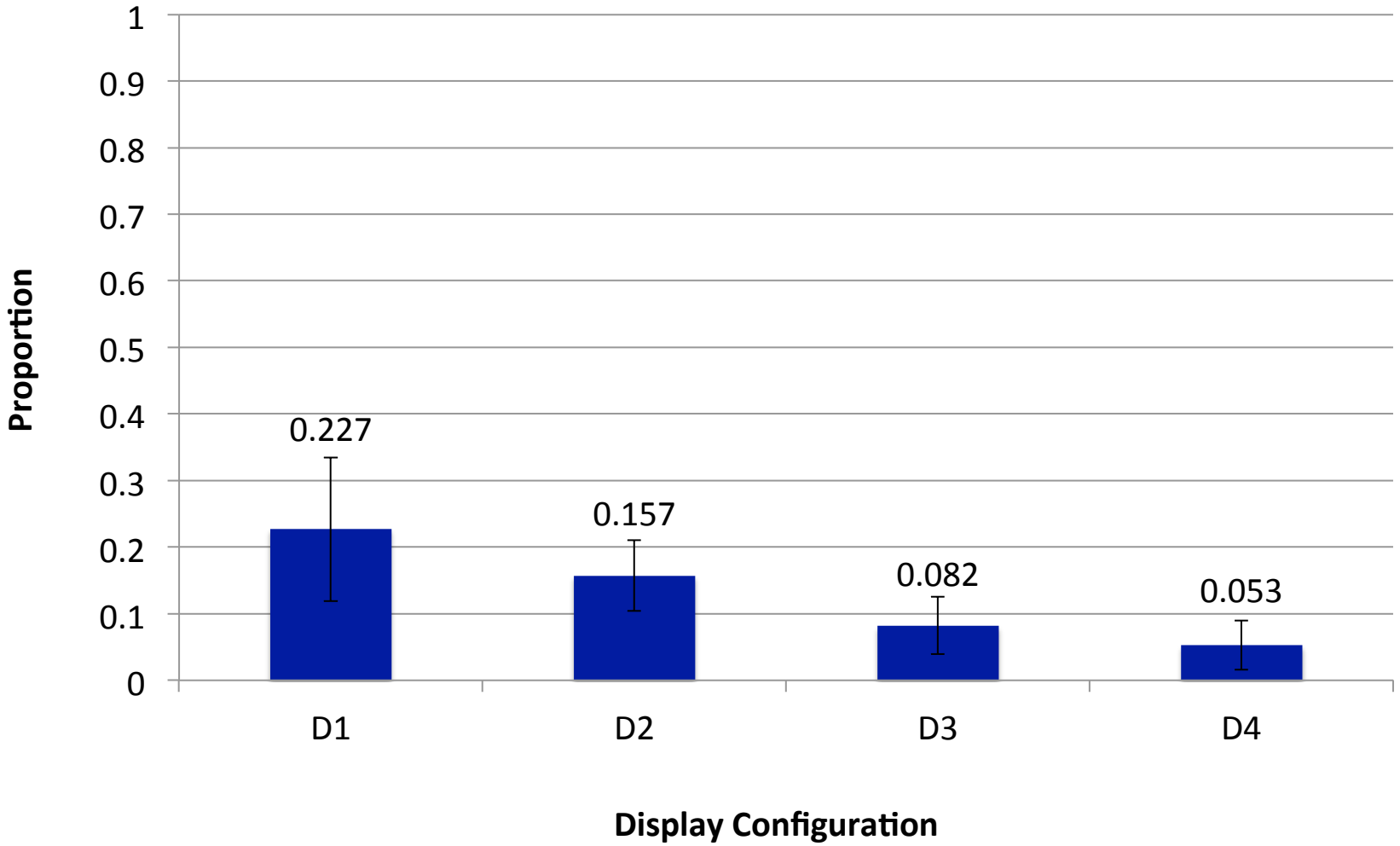
PT4 – Response Time Results



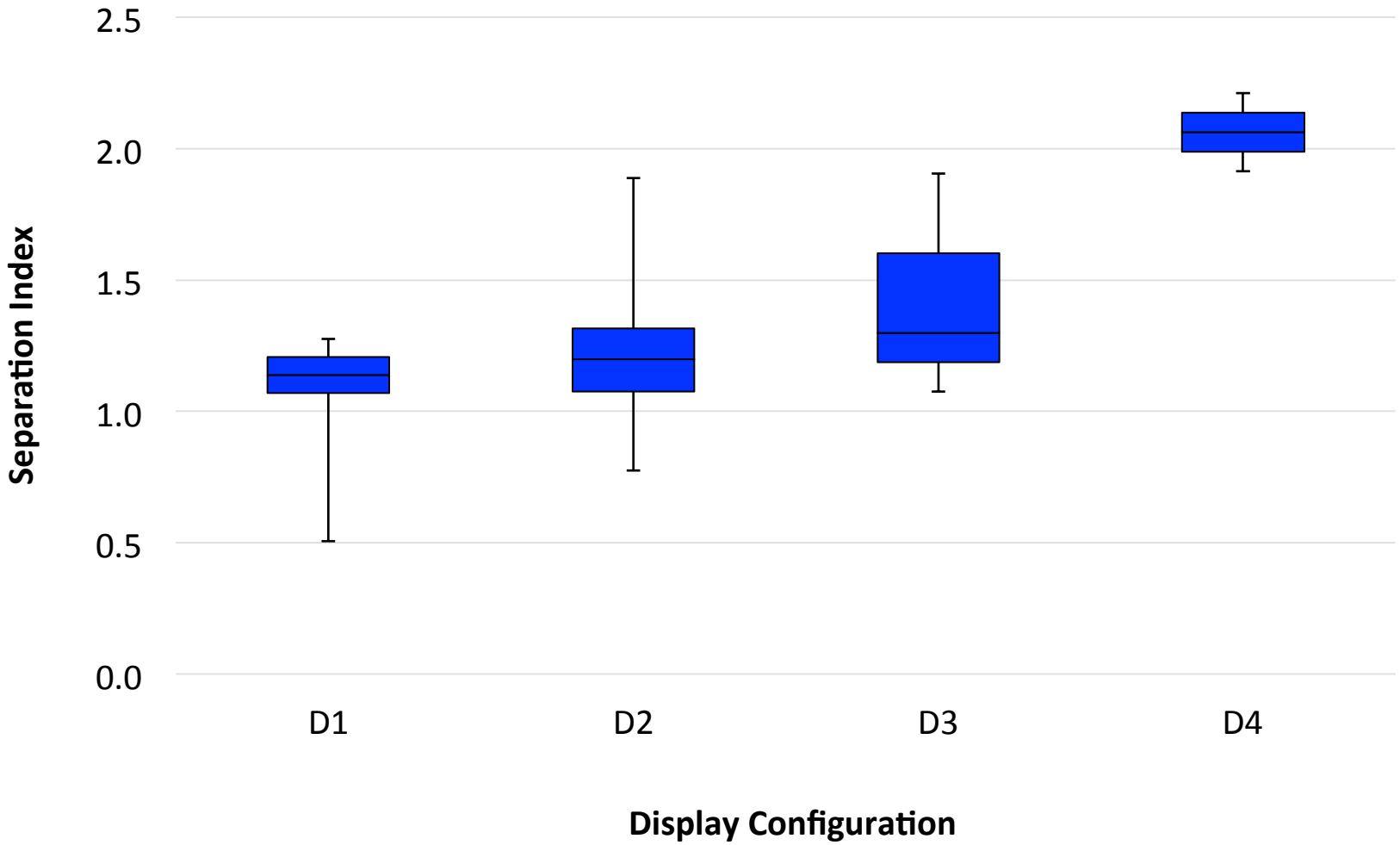
iHITL – Response Time Results



iHITL – Losses of Well Clear



iHITL – LoWC Severity



iHITL – Results Summary

- Total Response Time:
  - No significant differences between displays
  - Trend shows **Directive Only** and **Suggestive + Directive** as faster than Information Only and Suggestive Only
- Well Clear Metrics:
  - No significant differences between displays
  - **Information** and **Suggestive Only** (D1 and D2) display conditions had 2.5X as many LoWCs than the **Suggestive + Directive** combined (D4)
  - Severity data shows evidence of trends toward performance benefits with **Suggestive + Directive** compared to other three displays

PT5 – Overview

- Goal: Continue evaluation of candidate Detect and Avoid (DAA) displays and algorithms with respect to self-separation and collision avoidance to inform SC-228 DAA Minimum Operational Performance Standards
- Method:
  - Build upon results of previous hitl simulations results and lessons learned to identify minimum DAA display and guidance requirements for draft SC228 MOPS
    - PT4: Advanced better than Basic (but issues; well clear & display training, pop-ups)
    - iHITL: No significant differences between Advanced information features from PT4, but trends favoring combined **Suggestive + Directive (D4)** guidance
    - Maneuver Study (AFRL): Banding display showed faster response time compared to informative and directive displays; banding and advanced informative had least losses of well clear (neither results statistically significant)

PT5 – Experimental Design

- Mixed Factorial Design
  - *Display Configuration* (Within-Subjects Independent Variable):
    - Configuration 1: Minimum Information Set (No Guidance)
    - Configuration 2: Stratway+ No Fly Bands
    - Configuration 3: JADEM Omni Bands
    - Configuration 4: JADEM Vector Planning Tools
  - *Sensor Performance* (Between-Subjects Independent Variable)
    - Level 1: Perfect Surveillance Data
    - Level 2: Imperfect Surveillance Data
- Embedded Variable
  - *Intruder Equipage* (manipulated within each scenario)
    - Transponder-equipped (detected via UAS's ADS-B)
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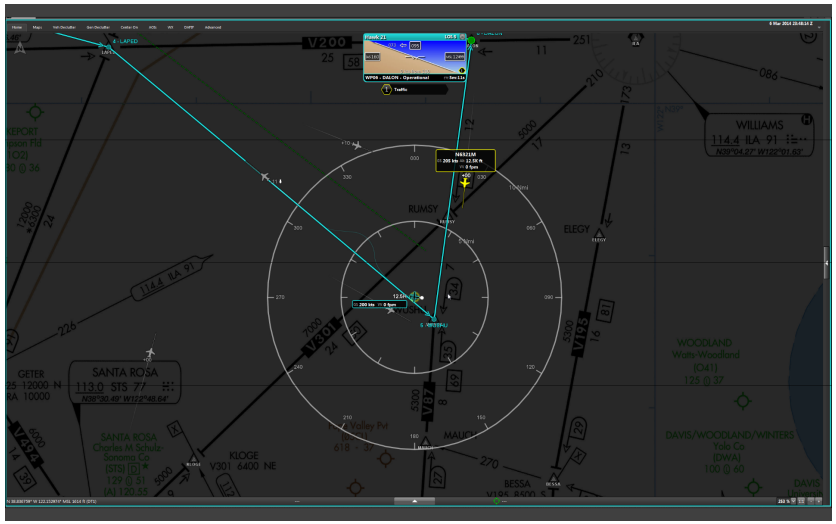
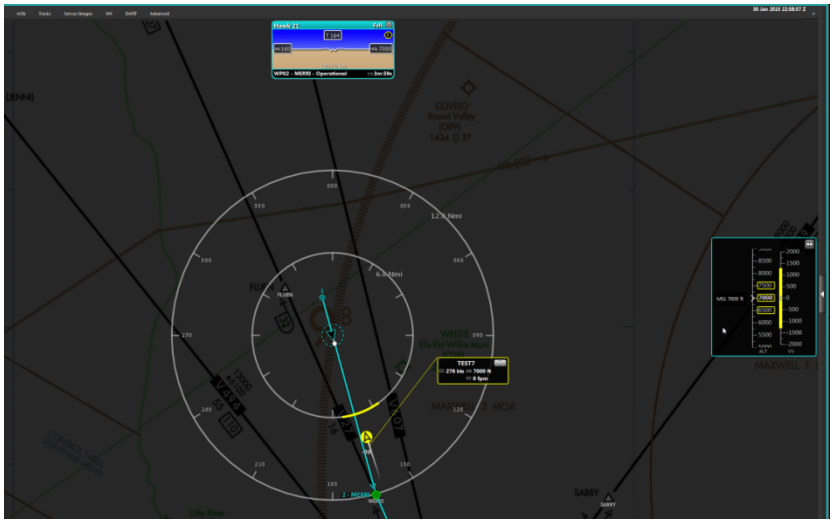
PT5 – Display Conditions

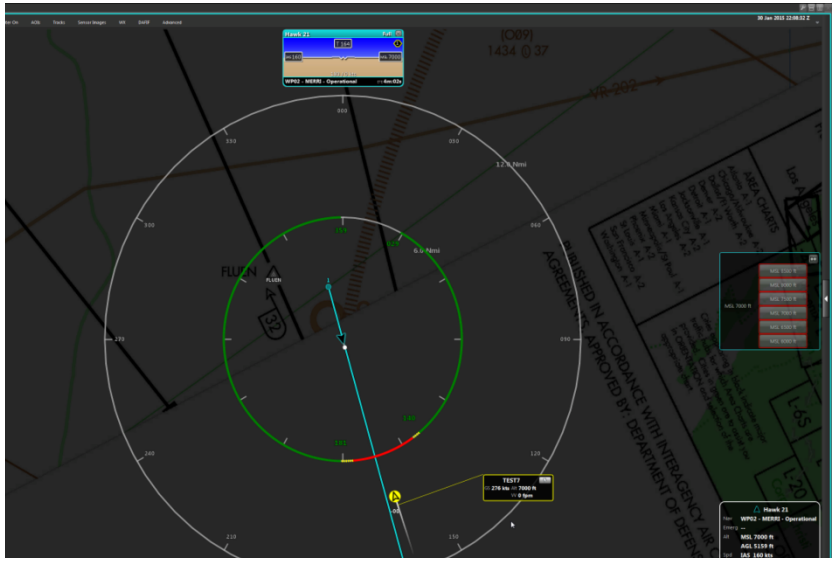
D1



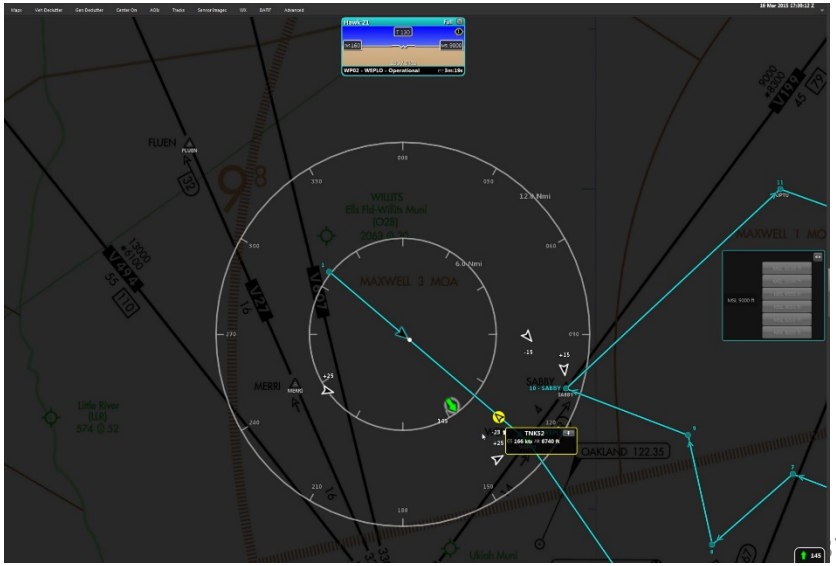
D2



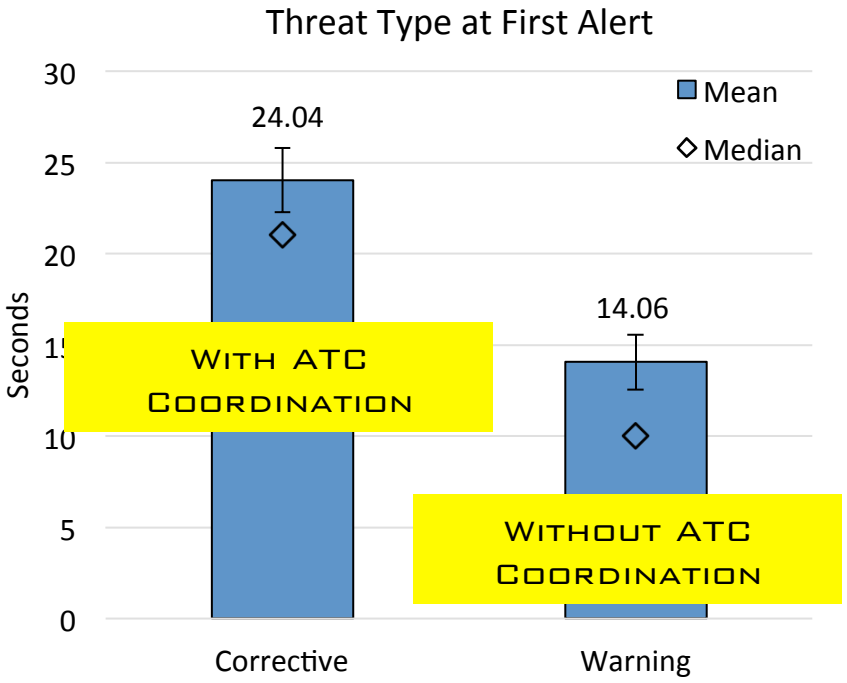
D3

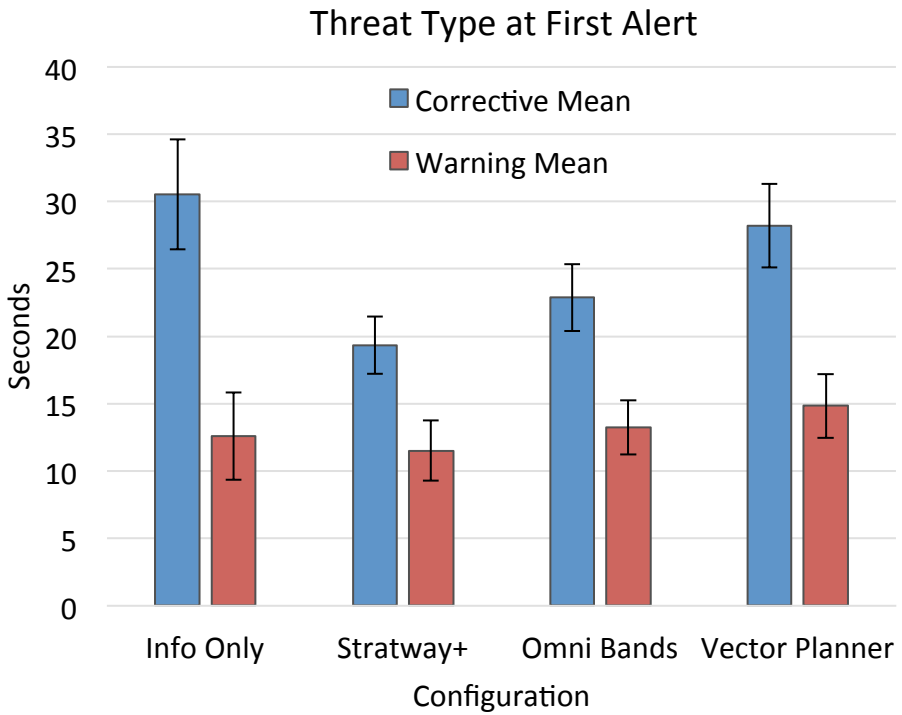


D4



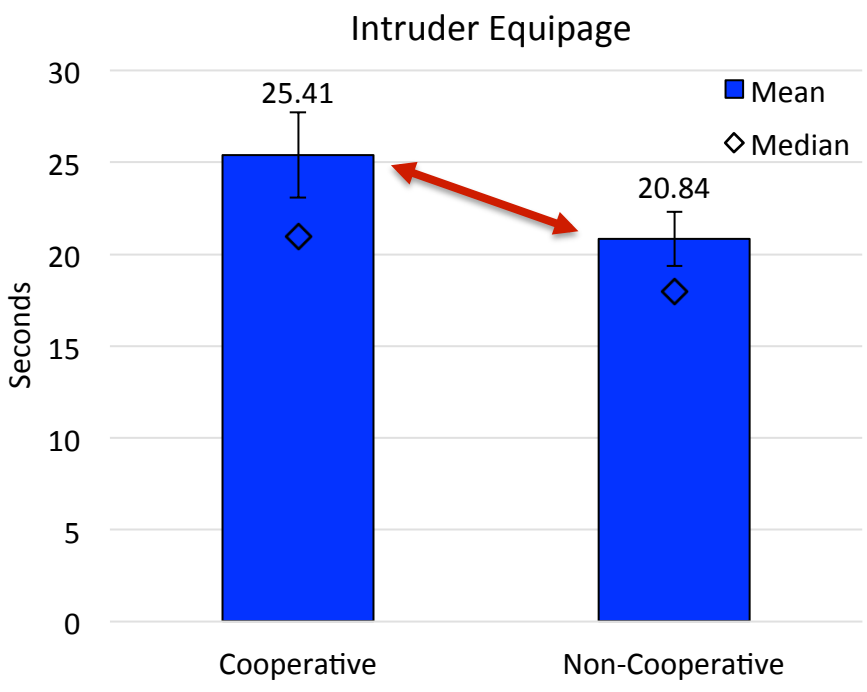
PT5 – Total Response Time Results

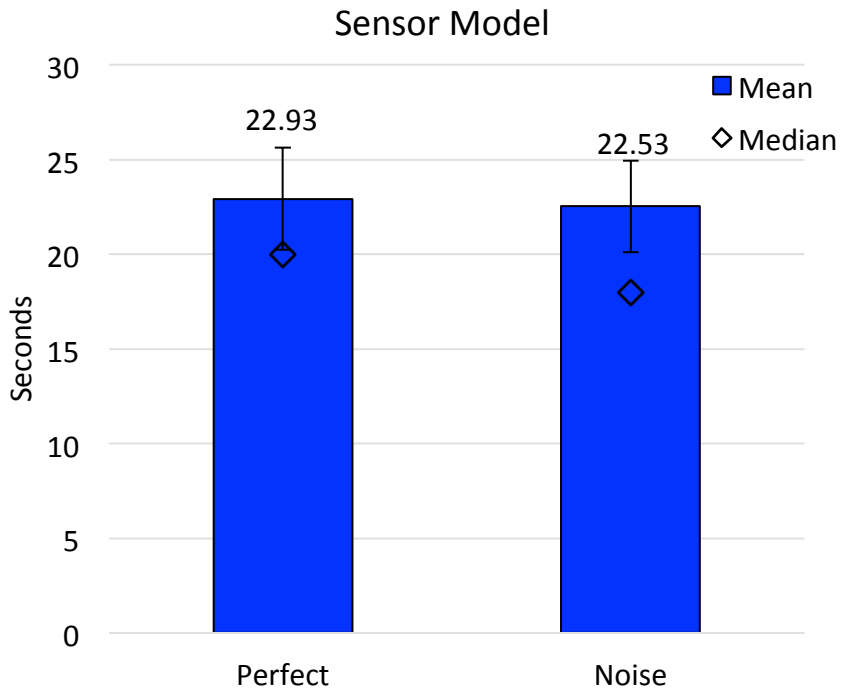




- Pilots responded, on average, **10s** faster to SS Warning Alerts than they did to Corrective SS Alerts
  - Pilots exhibited less variability between displays when responding to SS Warning Alerts than to Corrective SS Alerts
    - Range for SS Warning Alerts: 11s - 15s
    - Range for Corrective SS Alerts: 19s – 30s
  - Variability due to coordination with ATC – adds ~ 10 secs to total response time

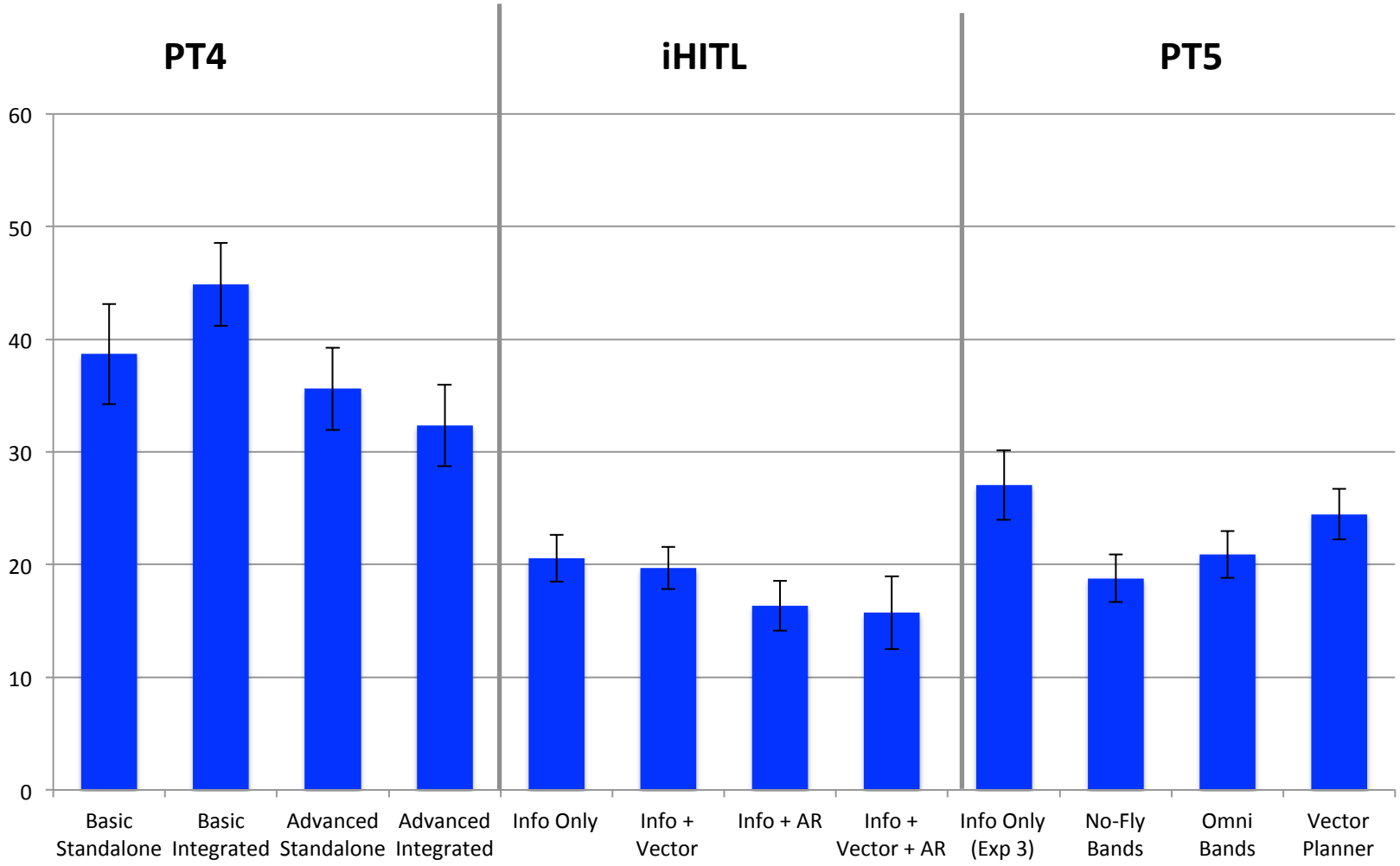
Total Response Time



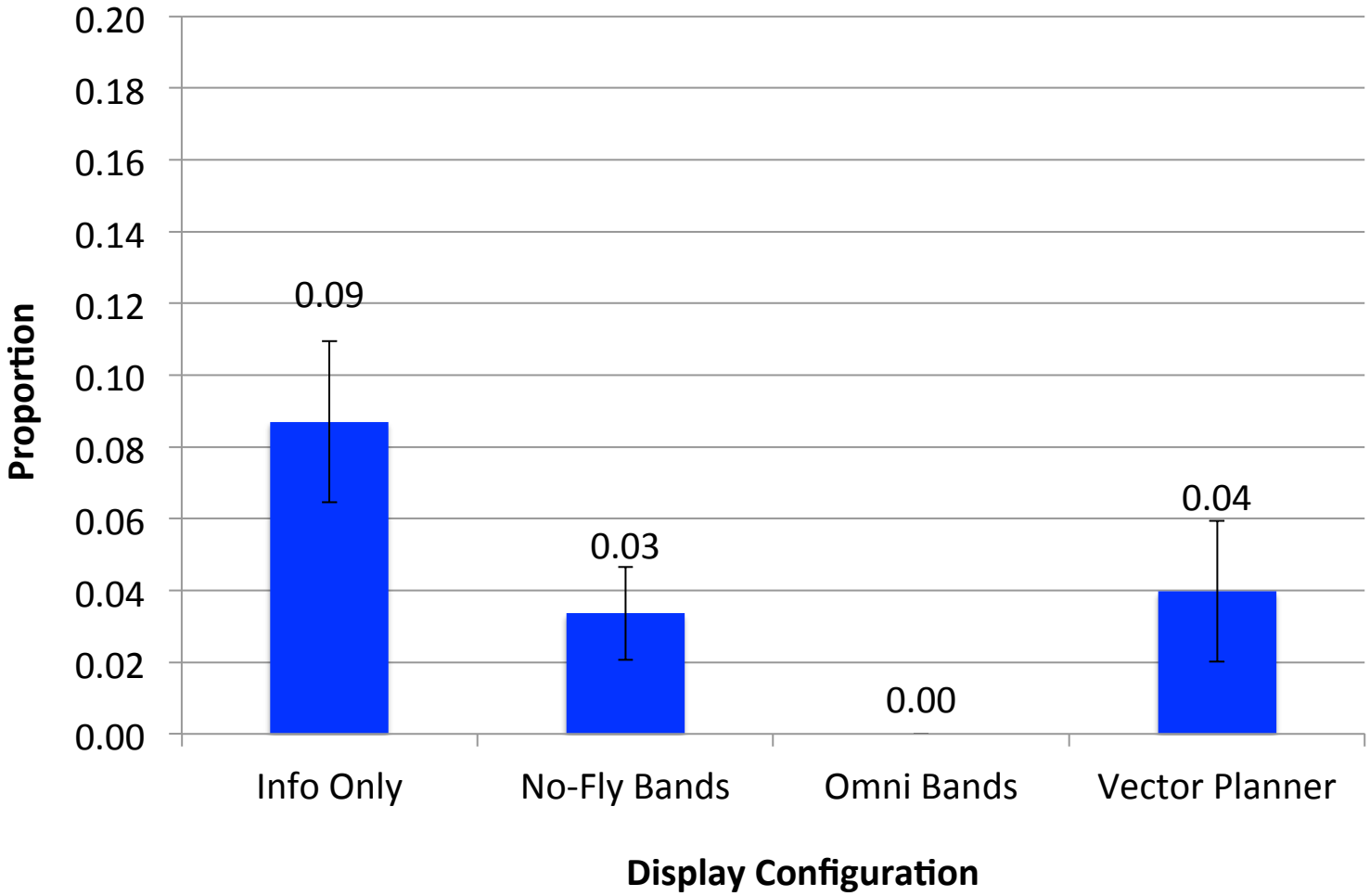


- Pilots responded, on average, **4.5s** faster to non-cooperative traffic than they did to cooperative traffic, which was a significant difference (p=.008)
  - There was also less variability in pilots' responses to Non-Cooperative encounters
- Sensor model was not found to have any effect on pilot's Total RTs

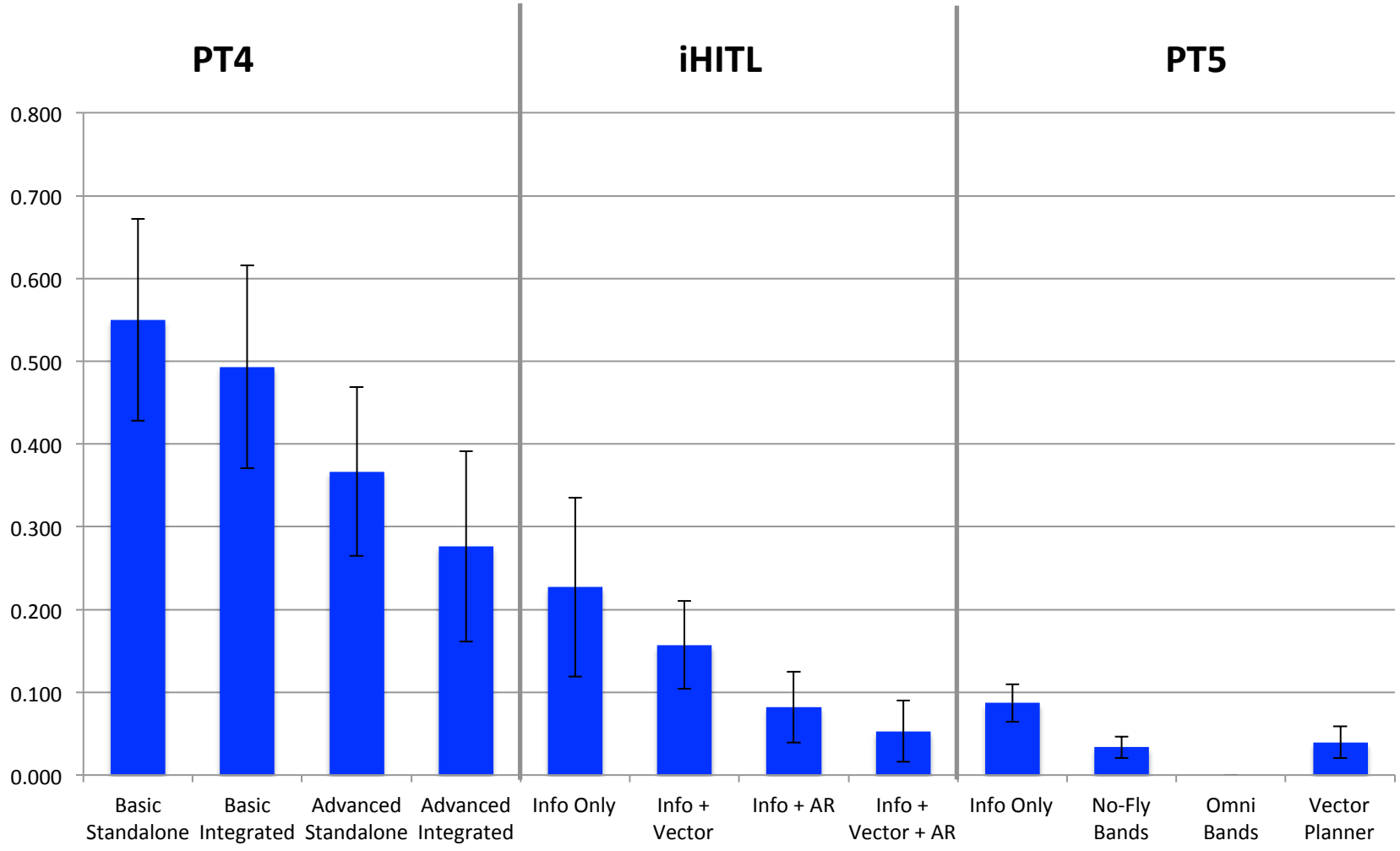
Total Response Times Across Simulations



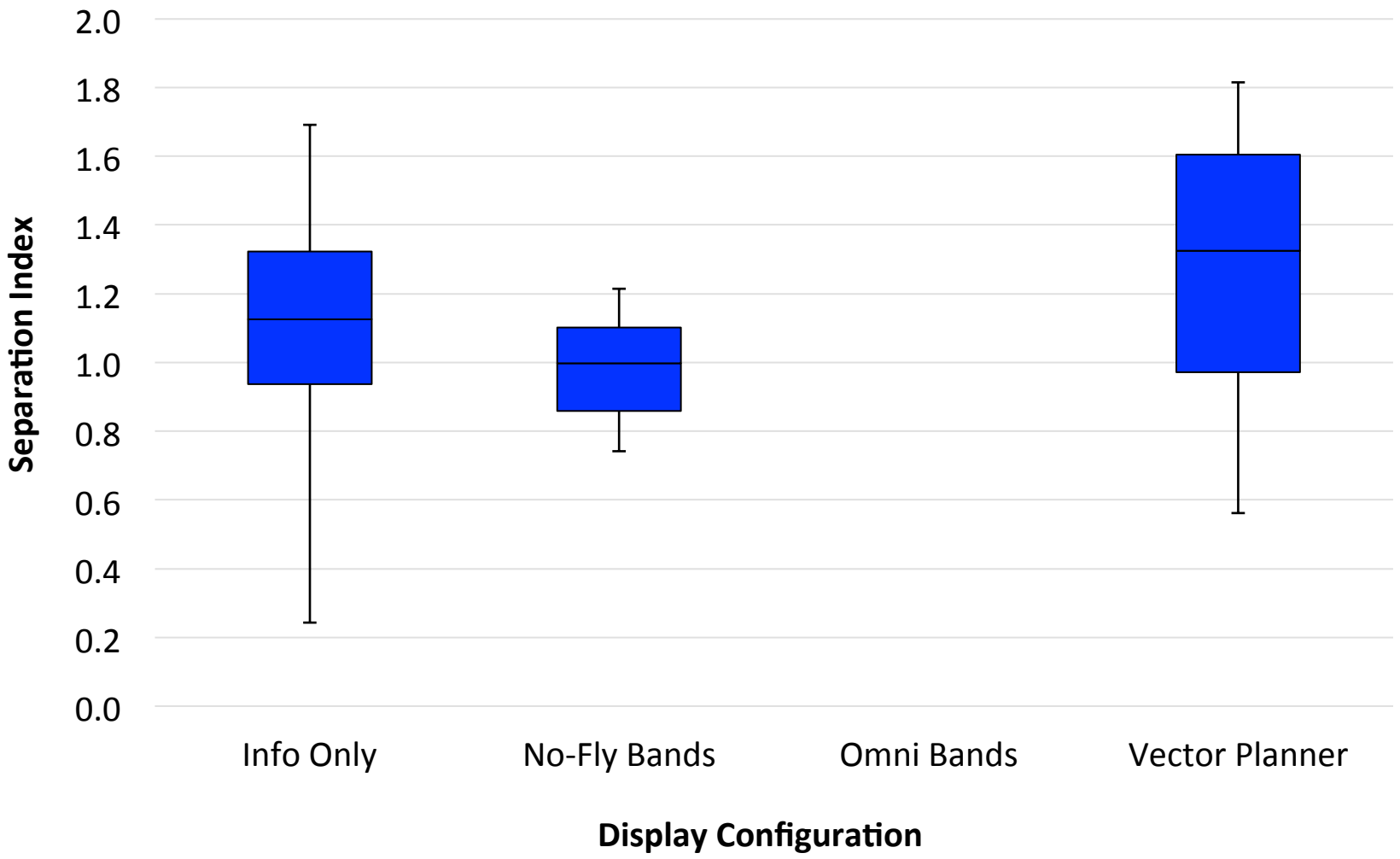
PT5 –Losses of Well Clear



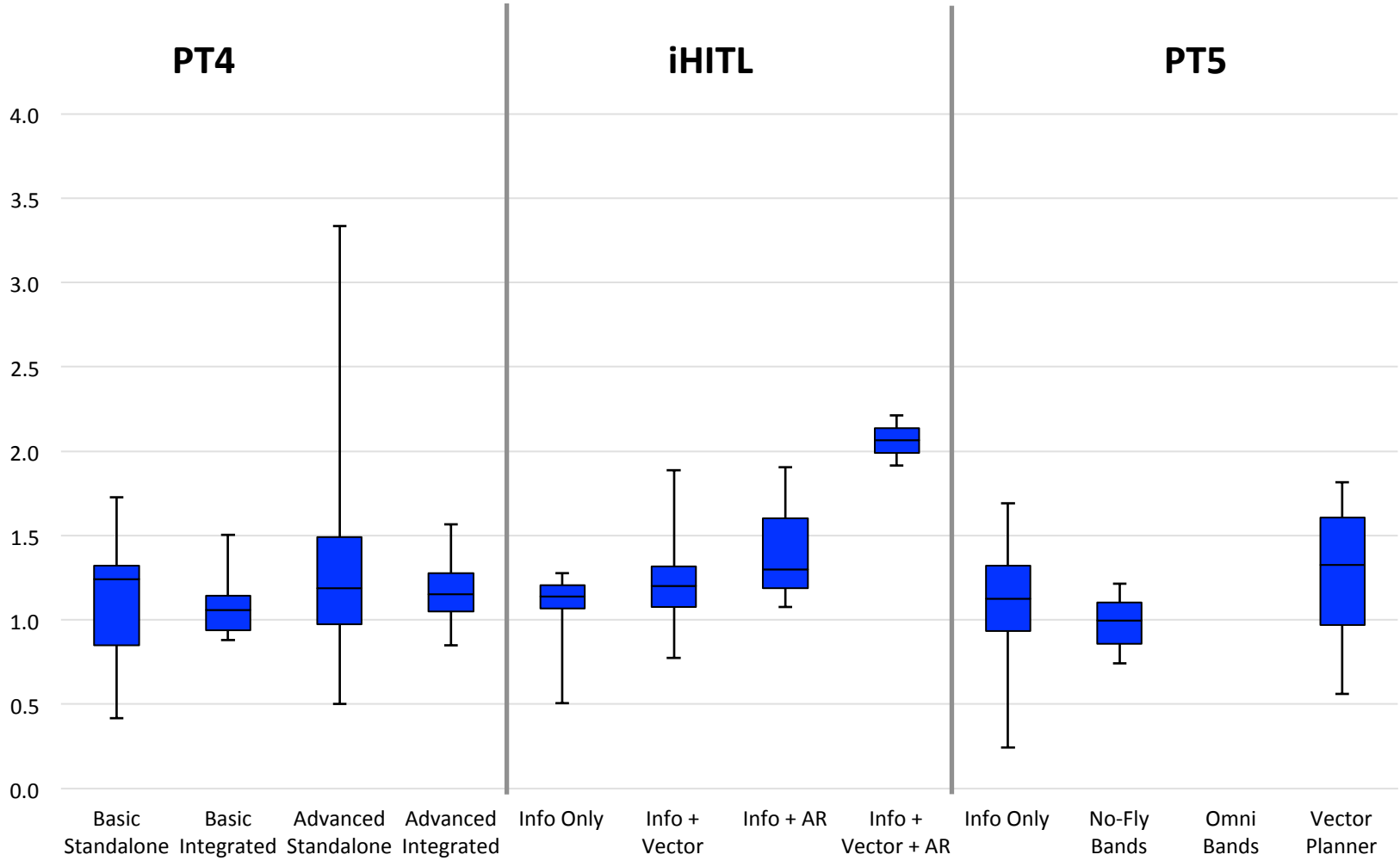
Losses of Well Clear Proportions Across Simulations



PT5 – LoWC Severity



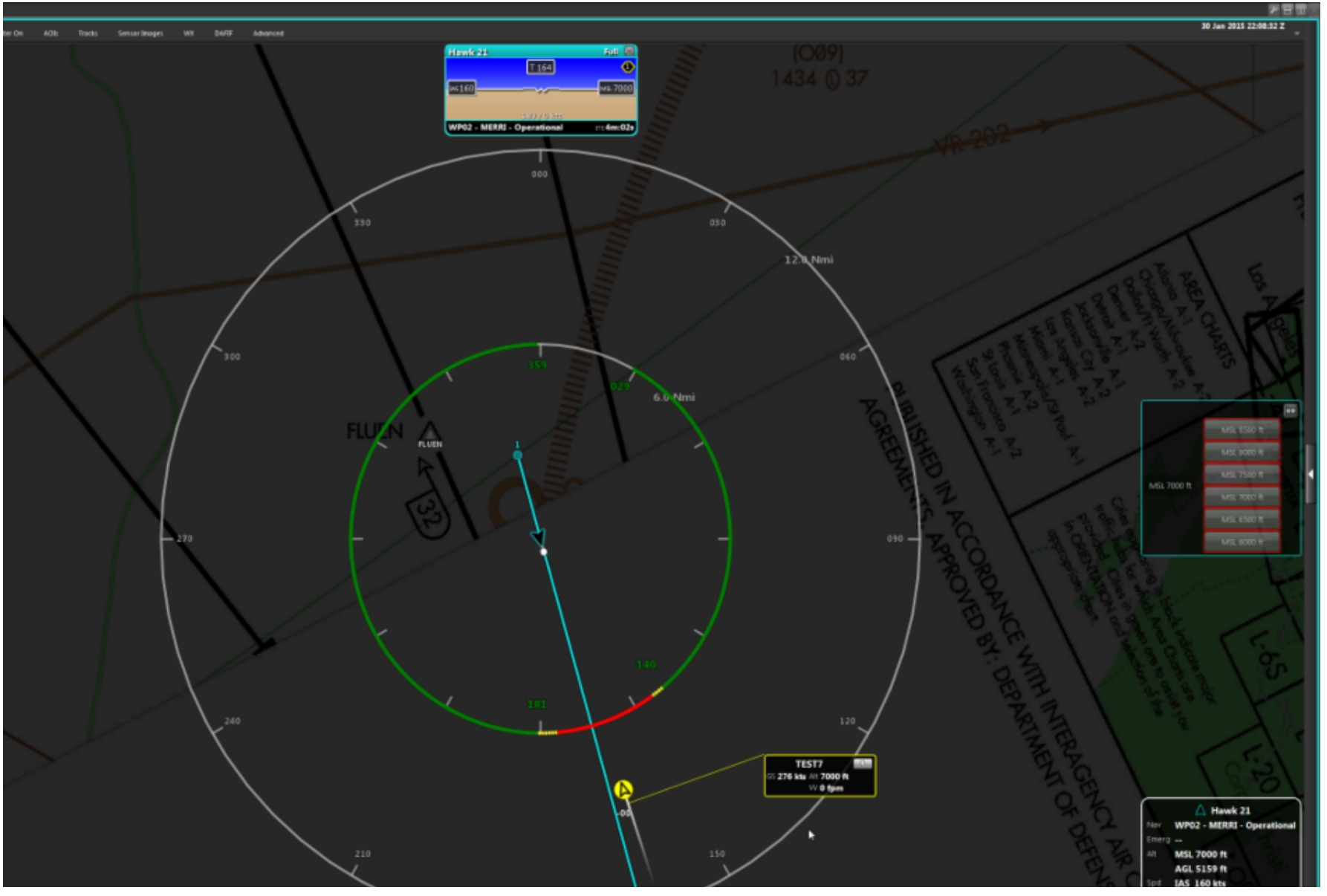
Losses of Well Clear Severity Across Simulations



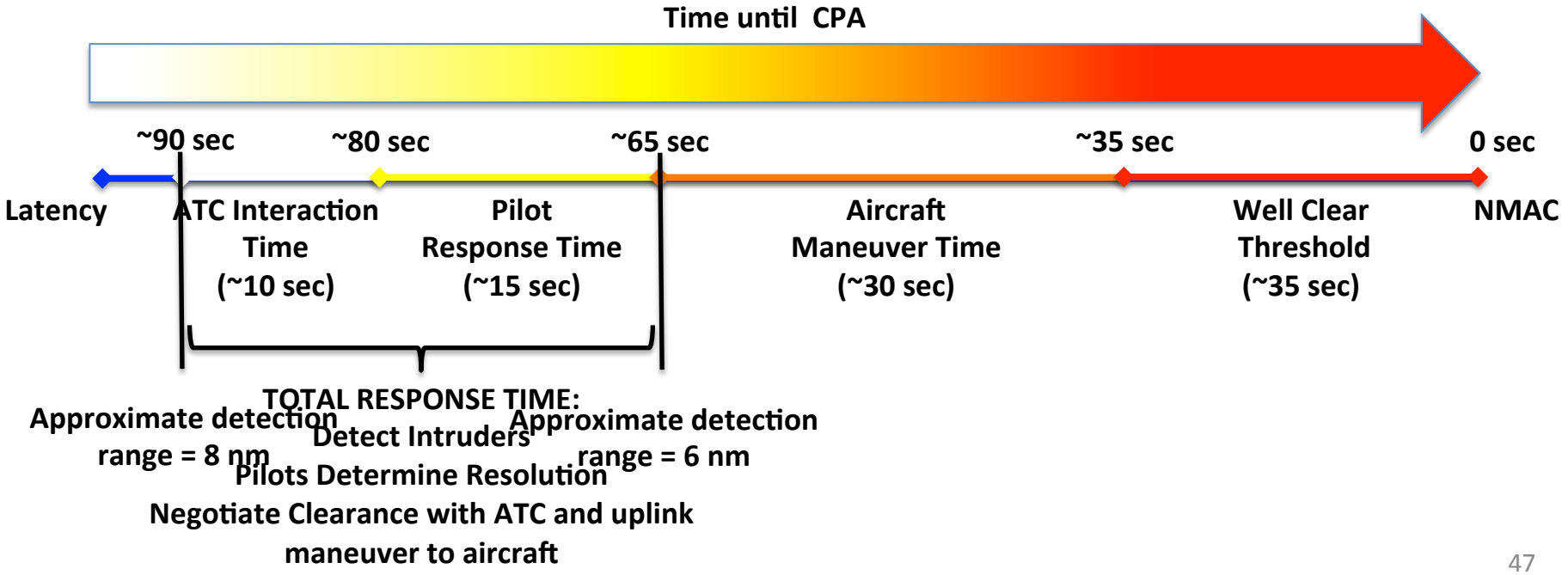
PT5 – Results Summary

- Suggestive guidance in the form of banding resulted in ***safer*** and ***more timely*** maneuvers away from conflicts
  - Lower overall proportion of LoWC for both banding displays (none for omni bands)
  - Least severe LoWC for both banding displays; most severe with info only
  - Shorter Total RTs for both banding displays
  - Pilots self-report as preferring the banding displays
- Results support decision for suggestive guidance as a minimum information requirement for DAA displays
  - Although Vector Planner display had similar performance, design approach not according to good HF principles and very poor performance compared to Omni Bands (despite same underlying algorithm)
- Results indicate that pilots can respond to a DAA Warning alert (no ATC coordination required) in ~ 15 seconds
- Results indicate that pilots can respond to a DAA Corrective alert (ATC coordination **is** required) in ~ 25 seconds
- ATC coordination adds approximately 10 seconds to DAA timeline

Suggestive Guidance Display – Example



Self-Separation Timeline



DAA-TCAS Interoperability HITL– Overview

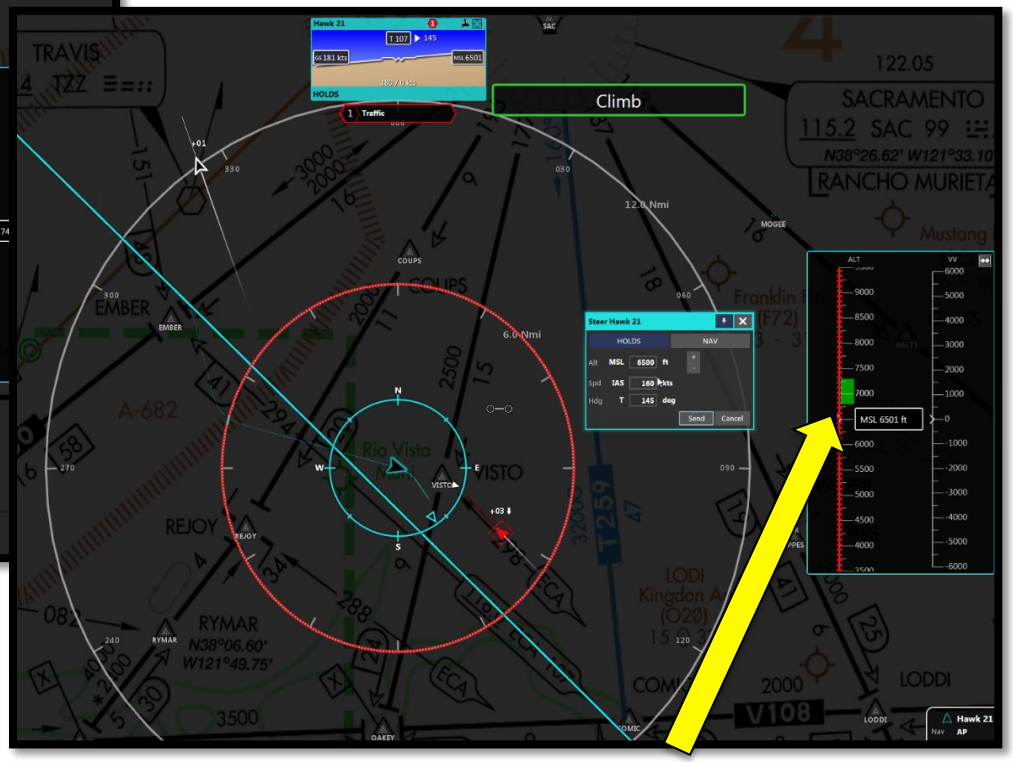
- Goal: Examine two remaining issues for SC-228 HMI MOPS
  - How to display “well clear recovery” guidance
  - How to interoperate with TCAS II
- Method:
  - Employ a part-task HITL design to examine pilot comprehension and performance responding to DAA and TCAS alerting and guidance near well clear and collision avoidance boundaries

Method: Experimental Design

- Mixed Factorial Design
  1. Well clear recovery/band saturation options (within subjects)
     - Limited suggestive/directive wedge
     - General directional
  2. Presence of green DAA banding (between subjects)
     - DAA guidance uses green banding to depict safe headings/altitudes
     - DAA guidance uses no banding to depict safe headings/altitudes
- Participants:
  - 6 active duty UAS pilots
    - Average Age: 36
    - Manned Flying Experience Total Hours: 1600
    - Unmanned Flying Experience Total Hours: 1400
  - 4 commercial pilots
    - Average Age: 30
    - Manned Flying Experience Total Hours: 9000

Method: Experimental Design

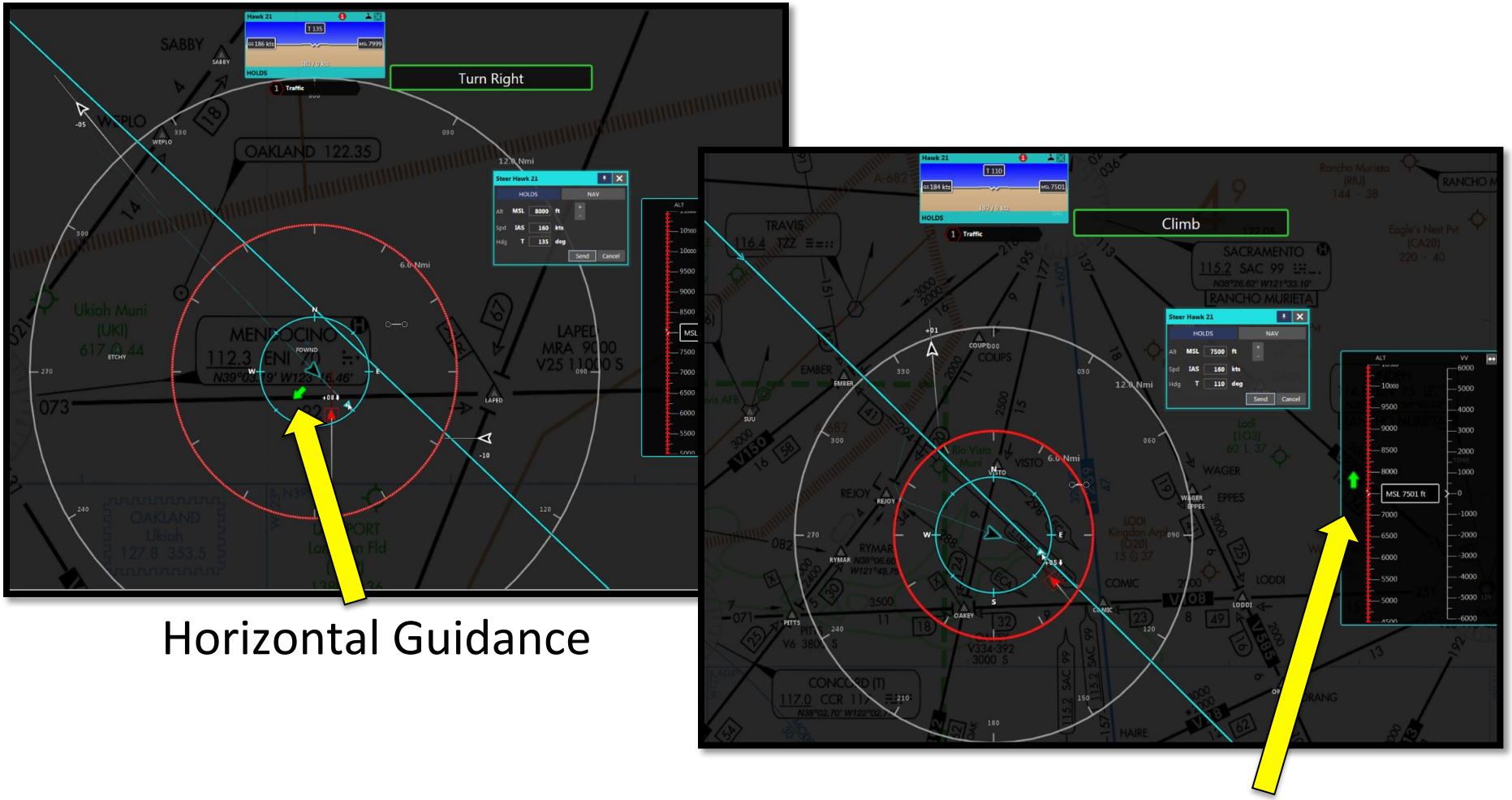
Horizontal Guidance



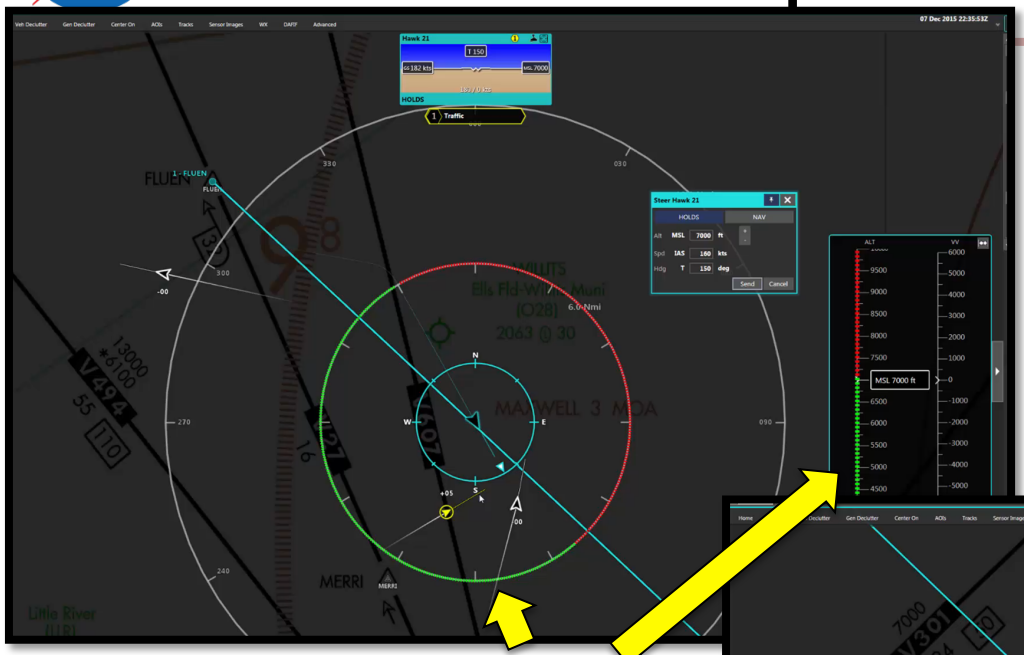
Vertical Guidance

Limited Suggestive

Method: Experimental Design



Method: Experimental Design

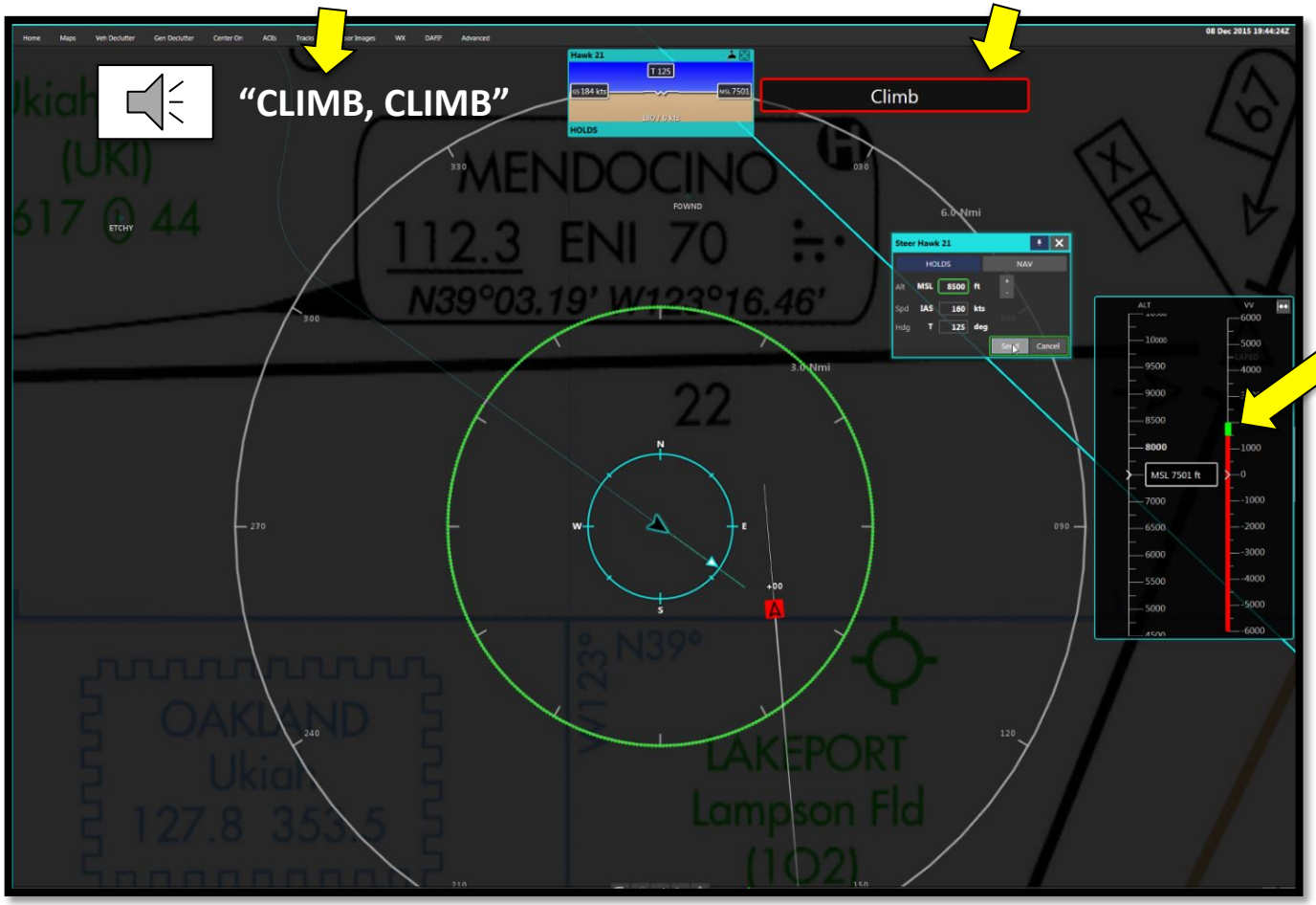


Green Bands

No Green Bands

Method: Simulation Environment

- Auditory Alert
  - RA sense presented aurally (source: TCAS II v7.1)
- Text Based
  - RA sense shown in text box next to Baseball Card



- Vertical Rate Guidance
  - Presented within VVI
  - Green = desired vertical speed
  - Red = vertical speed to avoid

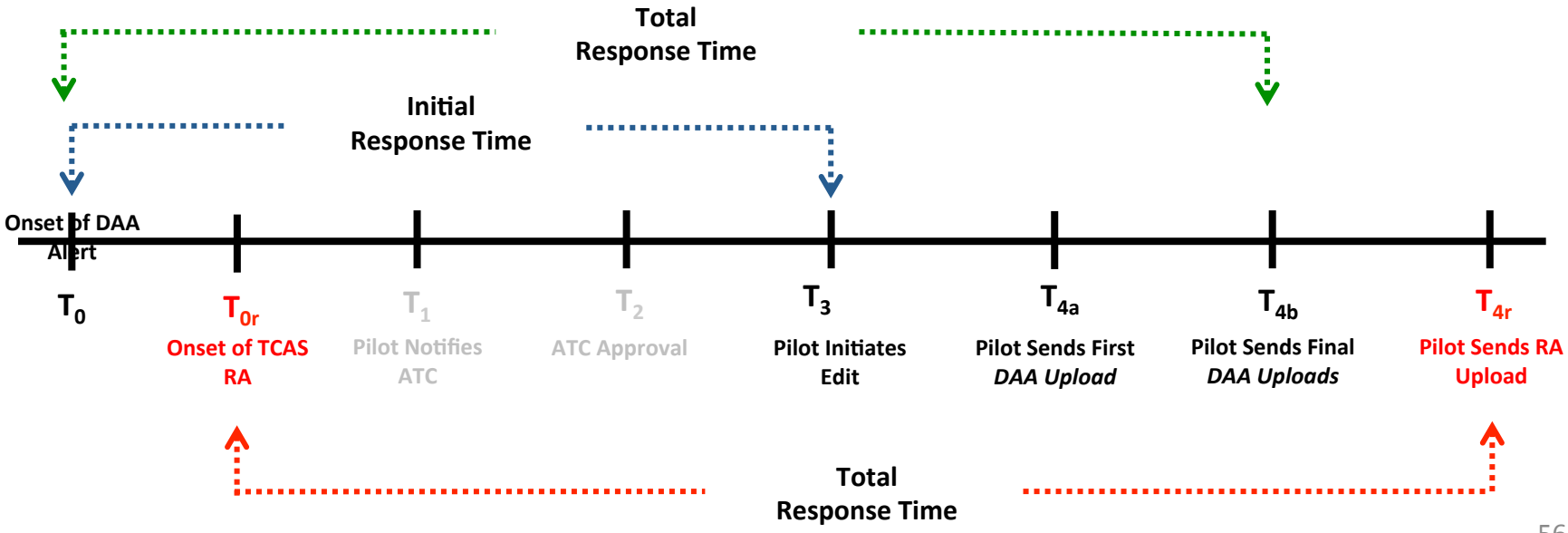
DAA-TCAS Alerting Structure

Symbol	Name	Pilot Action	Buffered Well Clear Criteria	Alerting Time Threshold	Aural Alert Verbiage
	TCAS RA	• **Immediate action required** • Comply with RA sense and vertical rate • Notify ATC as soon as practicable after taking action	(Driven by TCAS-II)	x	"Climb/ Descend"
	DAA Warning Alert	• ***Immediate action required*** • Notify ATC as soon as practicable after taking action	DMOD = 0.75 nmi HMD = 0.75 nmi ZTHR = 450 ft modTau = 35 sec	25 sec (TCPA approximate: 60 sec)	"Traffic, Maneuver Now"
	DAA Corrective Alert	• On current course, ***corrective action required*** • Coordinate with ATC to determine an appropriate maneuver	DMOD = 0.75 nmi HMD = 0.75 nmi ZTHR = 450 ft modTau = 35 sec	55 sec (TCPA approximate: 90 sec)	"Traffic, Avoid"
	DAA Preventive Alert	• On current course, corrective action ***should not be required*** • Monitor for intruder course changes • Talk with ATC if desired	DMOD = 1.0 nmi HMD = 1.0 nmi ZTHR = 700 ft modTau = 35 sec	55 sec (TCPA approximate: 90 sec)	"Traffic, Monitor"
	Remaining Traffic	• No action expected	Within surveillance field of regard	X	N/A

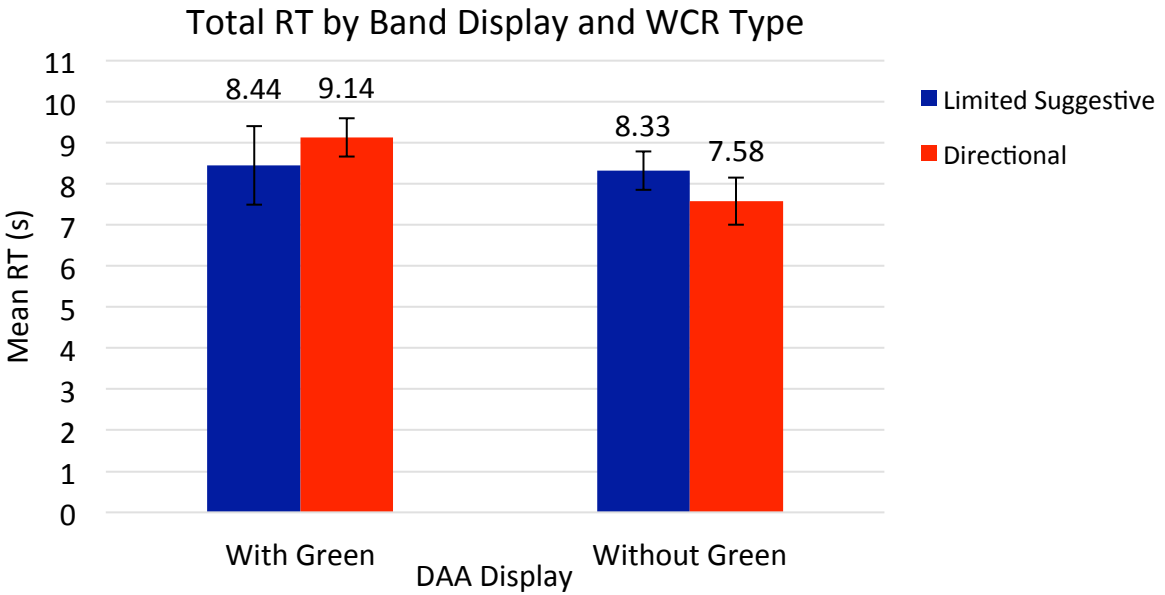
Videos

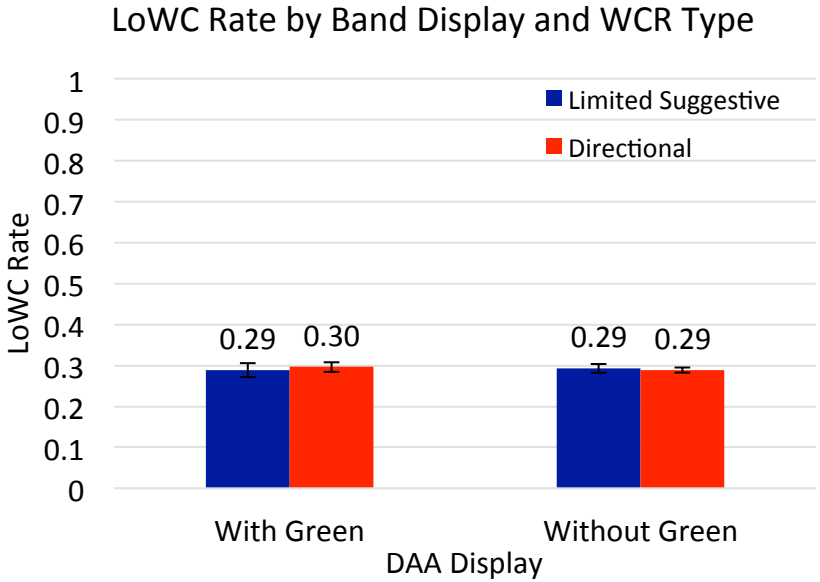
Metrics

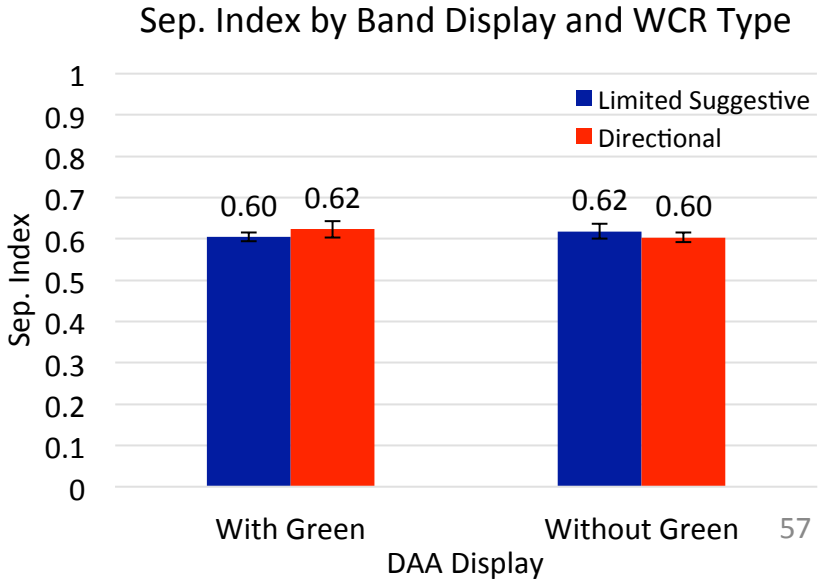
- Measured Response timeline modified slightly to account for “mini HITL” configuration
  - Pilot-ATC communications not recorded
  - Uploads in response to TCAS RAs given a dedicated timestamp
    - Allowed us to have measure of pilot responses to DAA and TCAS in the event they made multiple uploads



Well Clear Recovery and DAA Guidance Results

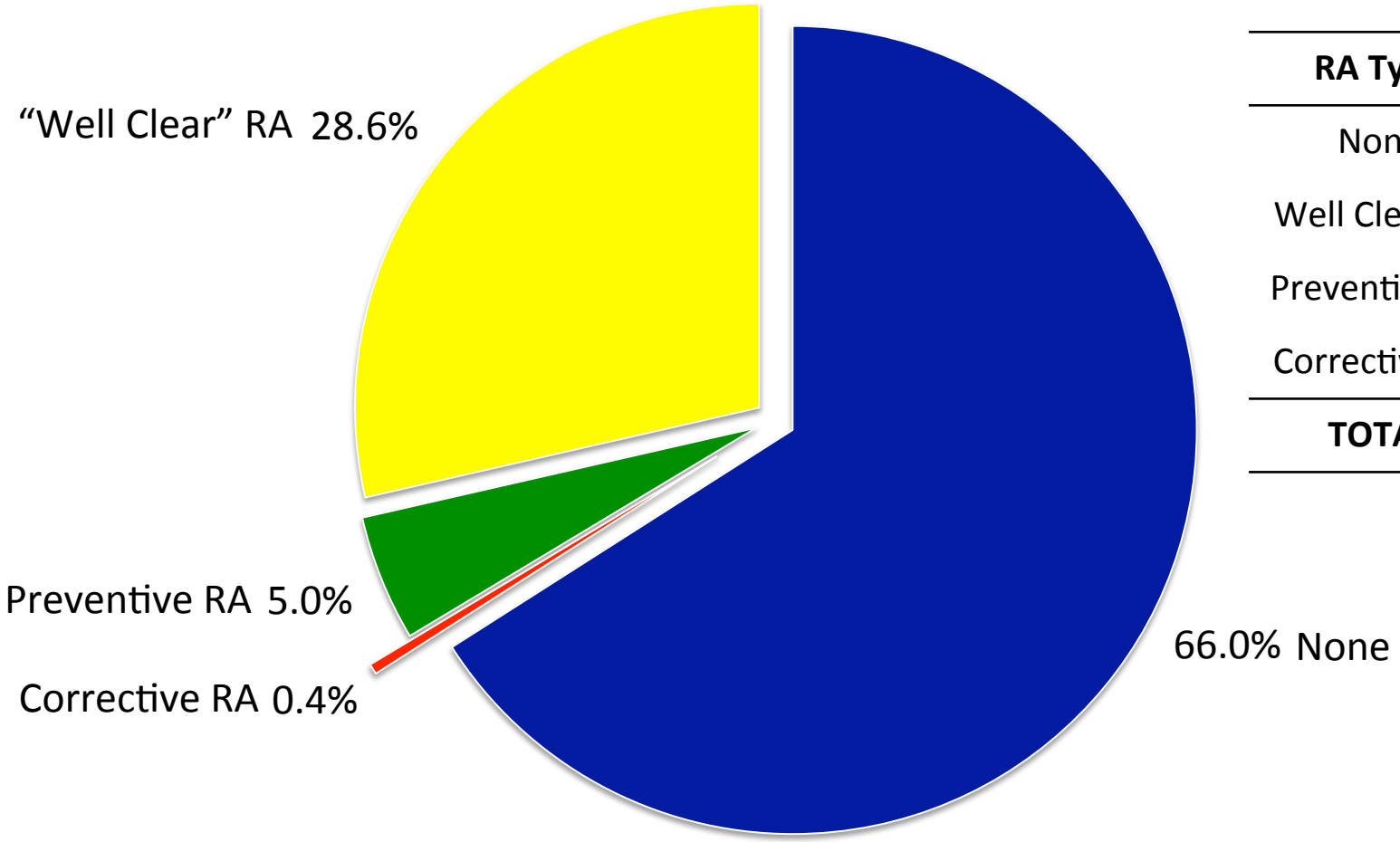






TCAS II Overall Results

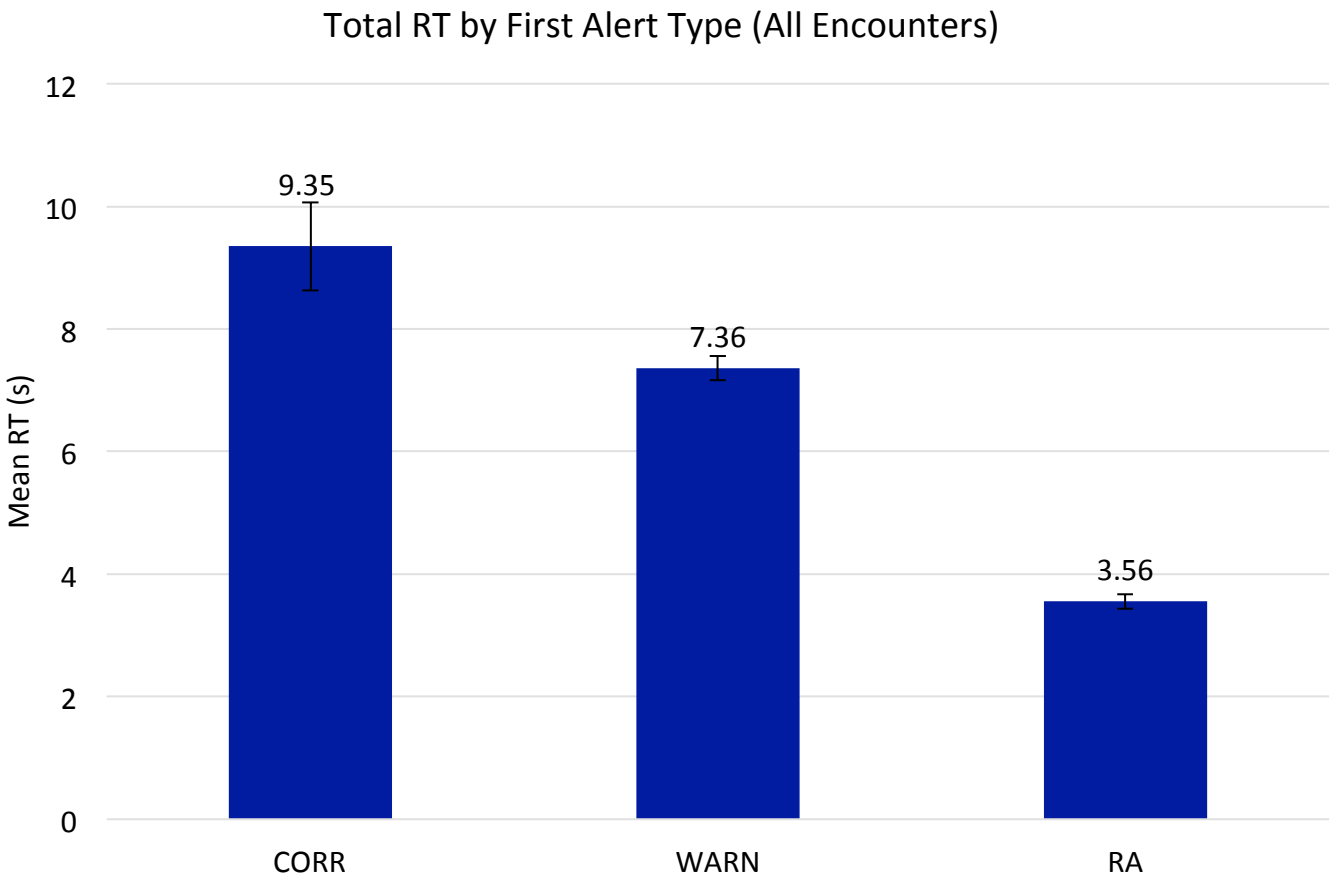
Occurrence of RAs (by type) when intruder did not blunder



RA Type	Number
None	157
Well Clear RA	68
Preventive RA	12
Corrective RA	1
TOTAL	**238**

TCAS II Overall Results

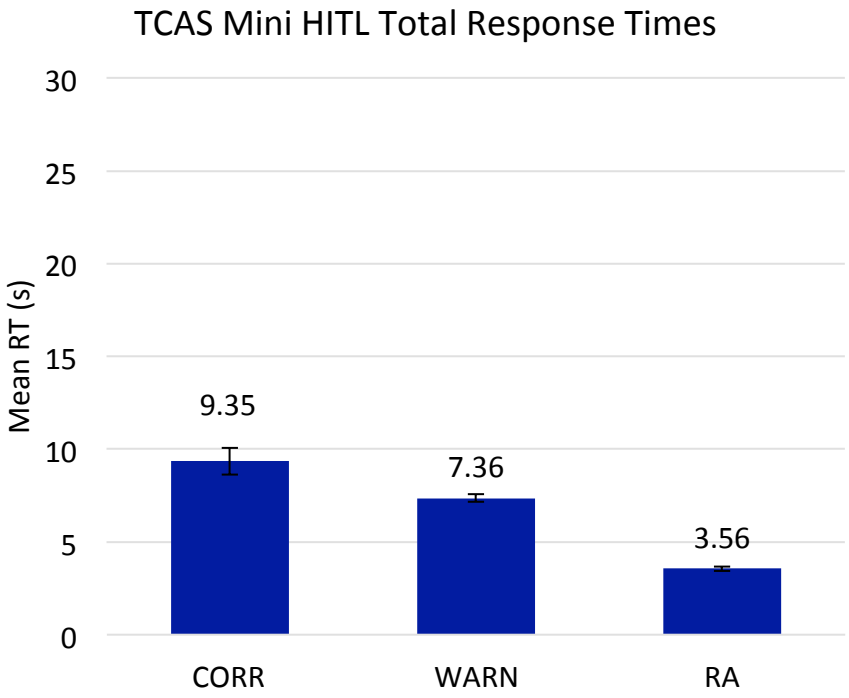
Pilot Total Response Time by Threat Type at First Alert

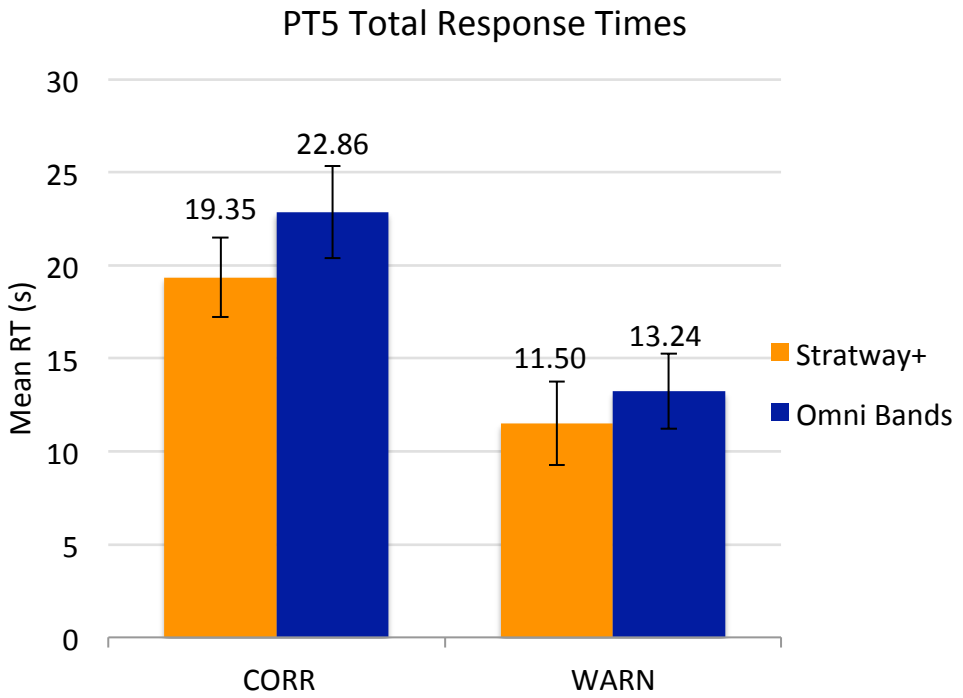


NOTE: ALL of the RAs at First Alert were ‘well clear’ RAs

TCAS II Overall Results

Pilot Response Time by Threat Type at First Alert
Comparison to PT5 Data





Discussion

- Overall, data provides support for the DAA-TCAS Interoperability concept developed at the TCAS Interoperability Workshop:
  - Pilots exhibit comprehension of, and appropriate prioritization within, the DAA alert structure with DAA warning alert and TCAS RA
  - Pilots show good compliance to well clear recovery and TCAS RA guidance
  - In many instances, pilots were able to prevent secondary conflicts with non-cooperative aircraft by inputting horizontal well clear recovery maneuvers prior to an RA being issued
- Instances of non-compliance reinforces key issue for DAA-TCAS Interoperability:
  - TCAS is unaware of non-cooperative aircraft and following RA guidance may result in secondary conflicts
    - This may cause pilots to non-comply or maneuver in opposite direction as TCAS RA guidance
  - Strong case for the need for ACAS Xu
- No substantive difference between different well clear recovery and DAA guidance displays
  - Allows flexibility for implementation by manufacturers

Discussion

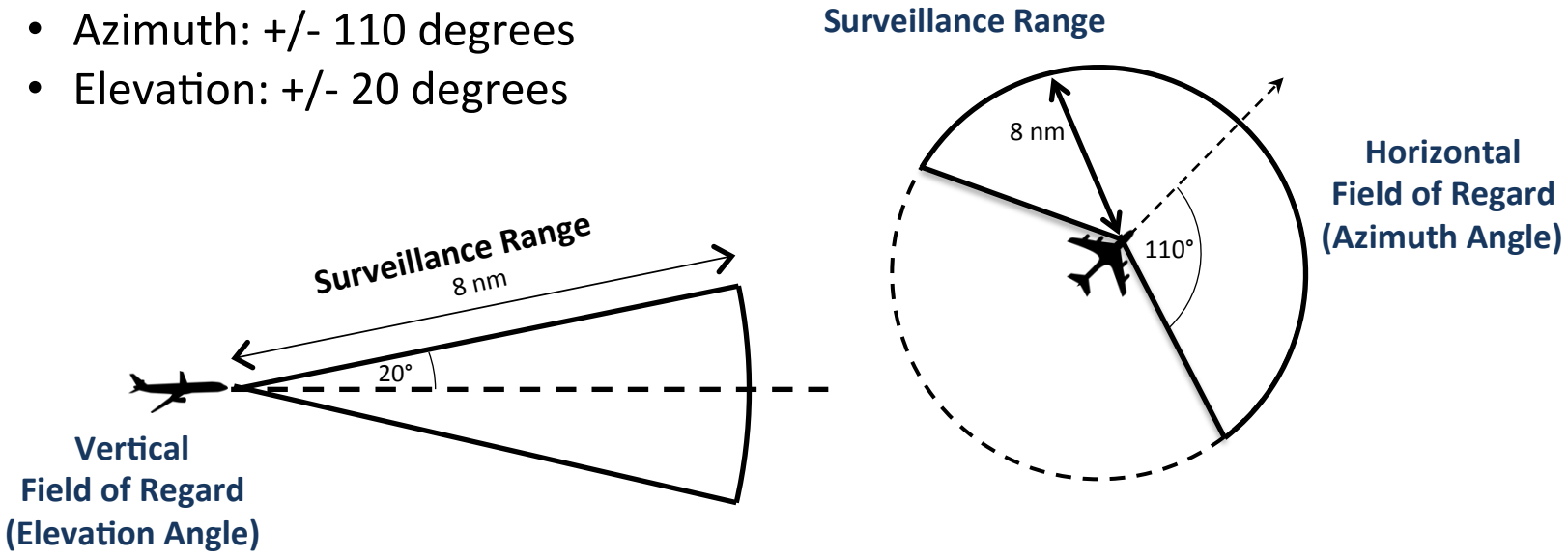
- Remaining Issues:
  - Data needs to be verified in more realistic operational conditions
    - Response times likely to increase in real operational conditions
    - PT6 and FT4 provide separate opportunities to test a subset of encounters from the mini HITL in full mission simulation and flight test environments
  - Potential improvements/modifications to Interoperability concept:
    - Suppression of vertical guidance for the “no green bands” DAA display may be problematic since no bands = absence of well clear conflict
    - Should horizontal guidance still be removed for the RA aircraft or does instances of non-compliance drive need to leave a horizontal well clear recovery option available for the pilot
  - Aural alert queuing versus suppression

Questions?

Backup Slides

Sensor Parameters

- Sensor Ranges
  - Simulated **cooperative** sensor: ADS-R/TCAS-like ranges
    - Lateral Range: 15 nm
    - Vertical Range: +/- 5000 ft
  - Simulated **non-cooperative** sensor: based on state-of-the-art airborne RADAR
    - Lateral Range: 8 nm
    - Azimuth: +/- 110 degrees
    - Elevation: +/- 20 degrees



Parameters for Noisy Cooperative Sensor

Noisy Cooperative Sensor ("Transponder")			
	Parameter	**Value**	**Unit**
Field Of Regard	Range	15	nmi
	Azimuth	360	deg
	Elevation	+/-90	deg
Accuracy	Range Error Mean	0	nmi
	Range Error Std. Dev	0	nmi
	Range Moving Avg. Window Size	1	measures
	Azimuth Error Mean	0	deg
	Azimuth Error Std. Dev	2	deg
	Azimuth Moving Avg. Window Size	3	measures
	Altitude Quantization	100	feet
	Altitude Moving Avg. Window	6	measure

Yellow denotes the noise model variables that will used for PT5.

Parameters for Noisy Non-Cooperative Sensor

Noisy Non-Cooperative Sensor ("Airborne Radar")			
	Parameter	**Value**	**Unit**
Field Of Regard	Range	6	nmi
	Azimuth	+/-110	deg
	Elevation	+/-20	deg
Accuracy	Range Error Mean	0.008	nmi
	Range Error Std. Dev.	0.001	nmi
	Range Moving Avg. Window Size	1	measures
	Azimuth Error Mean	0	deg
	Azimuth Error Std. Dev.	2	deg
	Azimuth Moving Avg. Window Size	3	measures
	Elevation Error Mean	1	deg
	Elevation Error Std. Dev.	1	deg
	Elevation Moving Avg. Window Size	6	measure

Yellow denotes the noise model variables that will used for PT5.

Parameters for “Perfect” Cooperative Sensor

“Perfect” Cooperative Sensor (“ADS-B”)			
	Parameter	**Value**	**Unit**
Field Of Regard	Range	15	nmi
	Azimuth	360	deg
	Elevation	+/-90	deg
Accuracy	Latitude Error	0	deg
	Latitude Error Std. Dev.	0	deg
	Latitude Moving Avg. Window Size	1	measures
	Longitude Error	0	deg
	Longitude Error Std. Dev.	0	deg
	Longitude Moving Avg. Window Size	1	measures
	Altitude Error	0	deg
	Altitude Error Std. Dev.	0	deg
	Altitude Moving Avg. Window Size	1	measure

Parameters for “Perfect” Non-Cooperative Sensor

“Perfect” Non-Cooperative Sensor (“Perfect Airborne Radar”)			
	Parameter	**Value**	**Unit**
Field Of Regard	Range	6	nmi
	Azimuth	+/-110	deg
	Elevation	+/-20	deg
Accuracy	Range Error Mean	0	nmi
	Range Error Std. Dev.	0	nmi
	Range Moving Avg. Window Size	1	measures
	Azimuth Error Mean	0	deg
	Azimuth Error Std. Dev.	0	deg
	Azimuth Moving Avg. Window Size	1	measures
	Elevation Error Mean	0	deg
	Elevation Error Std. Dev.	0	deg
	Elevation Moving Avg. Window Size	1	measure